Both-handed Manual Writing in 3D with Visual and Proprioceptive Feedback

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Stereograms are double images that yield 3D impressions if observed properly. This paper treats stereo writing and stereo drawing, a technique to produce stereograms manually by observing the emerging structures in parallel view; possibly these structures can already be perceived in 3D, as if writing or drawing would be done directly in a 3D medium. Though feasible, current results lack precision and thus, 3D perception of the product is difficult, locally impossible, indicating that also the process was—at least temporary—not perceived as happening in 3D. This paper treats the specific problem of virtual 3D goal points, the constituting 2D-point pairs of which are often not reached both-handedly, likely since the visual system suppressed one half image, and visual feedback—relying only on a half image—signaled erroneously "goal reached". Is there a reliable way of sensing that a virtual 3D goal point has been reached, in other words, that the pen tips of both hands reached both of their 2D goal points? The suggested answer is: proprioception can yield such sensing. Writing leaves—besides visual marks—also physical marks, depressions in the paper that can be sensed by the hands: The pen acts as a transmitter for the perturbations of the pen tips entering these paper depressions. An example shows the applicability of the solution. However, also other alternative 2D visual modes had to be used and should be explored in the future for creating better stereograms manually: 3D perception might be rather the result from optimizing the manual production process of a stereogram under parallel view, than the way to produce good stereograms.

Keywords: both-handed writing, both-handed drawing , visual feedback, proprioceptive feedback, haptic feedback, stereogram, 3D vision

1. How can we write in 3D? And why should we?

It is assumed that the reader knows what stereograms are. Though the stereograms in this paper seem difficult to produce—most figures and letters were produced with two hands writing or drawing simultaneously—writing both-handed can grow from human capacities quite "naturally"; at least as "natural" as conventional writing with only one hand. Many people being able to do the latter could do the former as well. It might seem anachronistic to develop handwriting further, while technology seems to make handwriting soon obsolete. But possibly there is no better time than now for suggesting that manual writing deserves more research.

But why should we write or draw with both hands? The reason in this research: since we have two eyes that allow us to perceive the world in 3D. Thus, if one eye follows the lines made by one hand, the other eye those of the other hand, we can perceive our writing in 3D—under certain conditions that will be discussed later.

But for what purpose should we write or draw in 3D? Because we could express more directly

Wo TREFFE ich dich?
(neutral, stress on verb)

WO treffe ich dich?
(confirmation, stress on "Wo")

Fig. 1: "Where do I meet you?" in German, in Prosodic Writing (PW) visualizing linguistic *and* prosodic content of utterances. It is conceptually 3D, since it shows time (horizontal axis), pitch (vertical axis) and loudness (depth axis) in 3 spatial dimensions. PW might facilitate language acquisition. (Alphabet according to Herold 2017)

things we like to express. Current handwriting or manual drawing is only in 2D and therefore restricted, if we like to record higher dimensional concepts. Visualizing those in 2D requires a projection, which inevitably brings about a loss of information, whether we write down a spoken sentence in characters of an alphabet (loss of prosody), or whether we draw a house (loss of depth information). 3D writing or drawing could avoid, or at least decrease this loss.

One example for a concrete application of 3D writing is Prosodic Writing (PW): It is a writing style with transparent intonation ("pitch waves") and rhythm ("stress waves"), in short, with visible prosody. Pitch, in particular pitch accents, can be shown in the vertical; time phenomena, e.g. long sounds or pauses, in the horizontal; and loudness, e.g. stress patterns, in the depth dimension, through a "wavy" script with three kinds of variations (see Fig. 1). Loudness is here displayed by size variation (perspective), since our paper is only 2D.

In more technical terms: Pitch and loudness are visualized as transverse waves[1], time as a longitudinal wave[2]; these three waves "modulate" the carrier, the string of normal-sized alphabetical letters; the letters become displaced and deformed in a harmonious and meaningful way, harmonious[3] in order to guarantee legibility, and meaningful through its rather intuitive, systematic encoding and visualization of prosody.

2. Stereo writing and stereo drawing with 3D perception?

This section introduces both-handed writing and drawing, and its usage for writing or drawing perceptually in 3D. Both-handed writing has been explored and even taught in the past occasionally:

> The teachers at Eton tried to introduce the system of both-handed writing, but stopped it when an eminent scientist told them that by developing both sides of the brain at once it would be likely to make idiots of the boys. Some public men have apparently been taught on this principle in days which were younger. (The Register, Adelaide, 1919)

Already before, in the 19th century, Fowler (1881) tried to develop a more efficient way of stenography, for example by writing both-handedly. After practicing the left hand, he suggests to write with both hands simultaneously, however not from left to right, but from bottom to top close to each other in parallel, the left in mirror writing. His book could be found under www.

forgottenbooks.com, but not in Google Scholar, suggesting that the reception of his approach was limited.

Scientific publications on both-handed writing or drawing from the late 20th or 21st century could not yet be found, a more thorough search might be necessary.

In this research, left and right hand move synchronously, writing almost the same letters (no mirror writing of the left), or drawing almost the same lines. Therefore, *stereo writing* or *stereo drawing* are suggested here as more specific terms to describe this technique. The writer looks at the page in parallel view (a common mode to watch a stereogram) during writing or drawing. The base distance of the pen tips is usually held constant on one page of paper and somewhere between 35 mm and 70 mm; it must not exceed the eye distance of the observer, because humans usually cannot diverge their eyes beyond parallel lines of sight, though some divergence can be achieved by training: Hermann von Helmholtz wrote that he could produce a divergence of his lines of view up to 8 degrees[4] (Helmholtz 1867, 475).

Applying parallel view, a stereo writer actually might perceive just *one* line, as long as he keeps the distance of right and left pen tip constant and draws the lines synchronously. Parallel view causes both, the left line seen by the left eye and the right line seen by the right eye, to be observable in the same region of the visual field, the brain can fuse them to one virtual line. In fact, the viewer can perceive even three lines, the one fused in the center, and two more, half images of a line to the right and left. But being just half images and peripheral, their presence is often not realized.

Let us consider the fused image in the center of the visual field: Any deviation from synchronous motion causes differential changes of the distance, *binocular disparities* occur. Grid paper helps keeping the distance constant, since it offers visually matchable structures from the beginning of writing or drawing.

Depth can now be achieved by slightly and deliberately changing the horizontal distance of the pen tips. If the distance gets smaller (negative horizontal disparity) the eyes of the observer have to converge for matching, and in natural scenes, this occurs when closer objects are focused: the brain interprets closeness. On the contrary, if the horizontal distance gets larger (positive horizontal disparity), our brain interprets growing farness. Horizontal disparity is the basis of *stereopsis* (binocular vision), allowing us to perceive the world in 3D.

And this is also in simple terms, how we can achieve 3D perception in our writing or drawing: it can emerge by carefully controlling the disparities between the two halves of the stereogram created: Precisely synchronous motions of right and left hand create identical, parallel figures that are located on a virtual plane similar to a real drawing plane. However, differential motions (or motion components) in the horizontal create horizontal disparity being interpreted by our brain as depth, if the interpretation yields meaningful 3D objects. (See also Rude 2016, 115 pp., or Rude 2017, Fig. 1)

For example, in Fig. 2, the inner squares of the right and the left image of the stereogram are further apart than the enclosing outer squares. When matching the outer squares in parallel view, there will be positive disparity between the retinal images of the inner squares, and consequently, they appear farther away than the outer squares. This perceptional depth phenomenon supports the interpretation of the whole scene as showing 3D wire cubes; cubes with the letter A, in block letters in the upper half, in cursive style in the lower half, located more or less on the faces of the

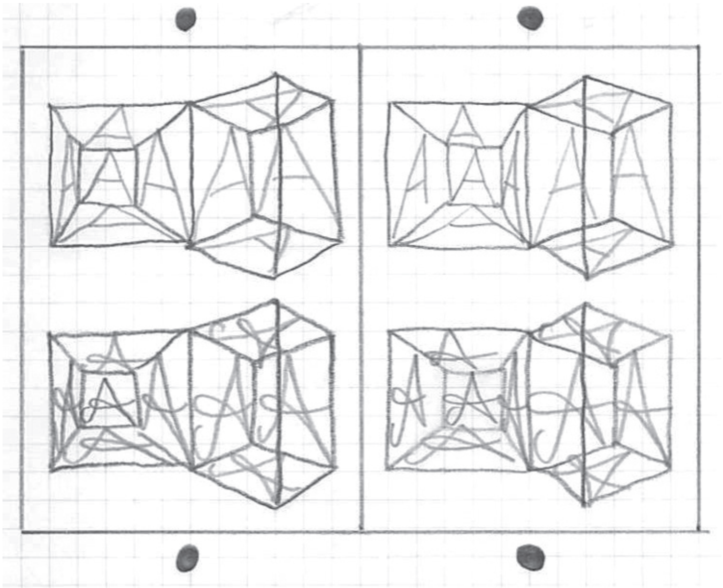

Fig. 2: Stereogram. Both-handedly drawn stereographical sketch of a wire cube in frontal view and edge view. On its faces are both-handedly written "A"s. Drawing & writing were done simultaneously with left and right hand under parallel view (left eye focusing the left image and v.v.). (Figure taken from Rude 2017)

cube.

Hint: practice to perceive some computer-produced stereograms in parallel view before trying the ones in this paper.[5] When you can perceive those in 3D, try these here: approach the figure with your eyes until the two black dots match, then slowly go back while continuing to focus the fused dots and try to accommodate.

Summary: This section explained how a stereogram can be drawn freehand, without mechanical aids or computer, by using grid paper and possibly reading glasses. The point is to use both hands simultaneously, to write or draw almost synchronously, and to observe the emerging patterns in parallel view, hopefully to perceive those in 3D. If the latter is the case, virtual 3D lines can be produced that lie in a virtual drawing plane, or that intrude in or extrude from it. In Fig. 2, such line segments compose wire cubes with the letter A. The figure is far from perfect, but it shows that the concept works in principle. (A simpler version of Fig. 2 without letters can be found in Rude 2017, Fig. 8)

3. Problems and research question: How to sense arrival unequivocally?

In the last section, the concept to manually write or draw both-handedly stereograms and to observe this process under parallel view was explained. Fig. 2 showed the principal feasibility of the concept. But it shows also a severe problem: lack of precision. The letter A should reach the edges or vertices of the wire cubes; this is achieved with satisfactory precision only in the upper left half image (drawn with the left hand).

The upper right image shows that some of the letter A’s legs do not reach their desired goal points, the vertices of the wire cube. While drawing the corresponding stereo-line segments, 3D perception obviously failed. One likely reason is the inability of matching some of the structures in the scene, and—in order to avoid *diplopia* (perceiving a double image of one object)—the suppression of one of the constituting half images in the brain. Possible candidates for suppression are the half images of the evolving lines or of the goal vertices.

A detailed analysis of the reasons is difficult. As a first step to solve the precision problem, we pose the research question as follows:

During stereo writing or drawing and while approaching a virtual goal point: Is there a reliable way to perceive online by human senses when the two pen tips reach the given goal points?

If human senses allowed clearly such a conscious judgment, if they produced a signal for each pen tip during motion execution (=online), then pen tip motion could be continued until the goal point is reached.

A solution of this question does not yet guarantee the successful creation of stereograms under 3D perception. However, it would avoid situations as in Fig. 2, where online visual perception likely signaled “3D goal point successfully reached”, but visual inspection shows in retrospect that this is not fact for at least one of its two constituting 2D points.

4. Solution: Using proprioceptive feedback in addition to vision

How to make sure that we reached two given goal points with both pen tips, irrespective of 3D viewing conditions? Let us start with a small experiment:

Please close your eyes and try slowly to approach and touch the tip of your nose with your index finger. Please try it once more, again blindly, now with the other hand. Now try it with both hands simultaneously.

Probably you succeeded. If so, you can surely confirm your success from a haptic sensation, from feeling the sudden contact in your finger(s) and your nose.

If your finger were very small and sensitive, you could use the same sense of touch to support the drawing and writing task from above: You could move your finger just next to your pen tip and feel to have reached the goal point; since these points are not only visible, but also perceptible by touch. Drawing the points left a trace, a small depression in the paper from the pressure of the pen tip on it.

Of course, our fingers are too big and not sensitive enough to feel the tiny depression. However, the pen tip itself is small enough and can transmit perturbations via the pen’s body. If using slightly thicker paper than usual and a soft support, and by exerting more pressure than usual in the end points of the line segments, tangible depressions will be created in the paper (similar to Braille). If a pen tip reaches and enters such a depression again, the related perturbations are transmitted through the body of the pen and can be felt by the writing hand, just like a pothole is felt through the body of a car by its driver. This feeling comes from proprioception, from sensations created in the muscles of our finger-hand system, signaling the “holing” of the pen tip into the depression.

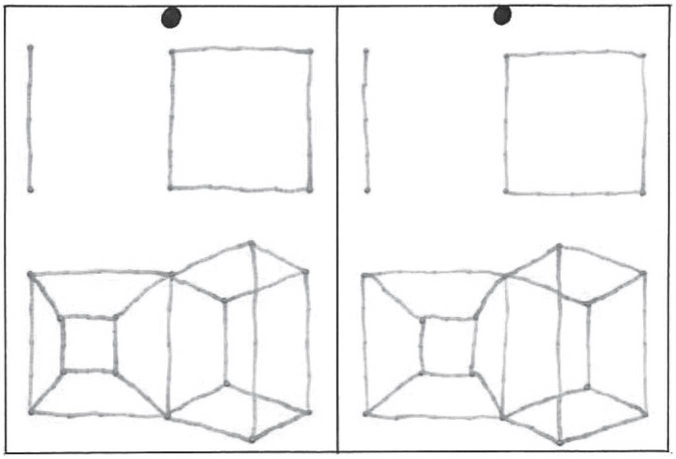

Fig. 3: Stereogram. Line segment (upper left), continued to a square (upper right), and then continued to two wire cubes (lower part). All segments were drawn in parallel view, but here by creating depressions in the paper at the vertices, which could later be used for proprioceptive feedback to signal the event "vertex reached".

Fig. 3 shows the wire cubes from Fig. 2 drawn again, now by creating depressions in the paper at the cubes' vertices through shortly resting there and pressing the pen downwards. First, the stereogram of a line segment is drawn (upper left in the 3D percept) with two depressions, one at each end point of the line segment. The square is completed counterclockwise (upper right) while producing two more depressions on its right side; its completion was felt when the upper line segments reached the upper left corners of the square, since the pen tip got stuck in the depression (the 4 corners of the square will become 4 vertices of the wire cubes). The drawing was finalized to two wire cubes (lower part), which are not only visible but also tangible via the pen tips in the 14 vertices (2 vertices are common to both cubes). All segments were drawn under parallel view. Since proprioceptive feedback is felt online, line segments can be continued until the pen tips are felt to have reached and entered the paper depressions of the corresponding 2D goal points, right and left. (A 5 mm grid paper was used between paper and support: it helps the visual system to keep a stable distance for parallel view; 60 mm in this example).

Many line segments seem to be composed of four strokes, since a variation of a technique from sketching described by Hoelscher and Springer (1961, 6-03) has been used. The authors recommend: "Experience has shown that it is very difficult to draw a long straight line in one stroke, whereas by using a series of short overlapping strokes a rough but straight line can be made readily. The sketch stroke, therefore, consists of a short light stroke made with an arm or finger movement as conditions dictate". Here, instead of using overlapping strokes, the four "stereo strokes" were drawn continuously, but interruptedly, with short rests in roughly equally spaced intermediate points.

Summary: This section was about how the arrival of the pen tips in the goal points (e.g. the wire cube vertices) can be perceived reliably by human senses. The solution: By proprioceptive feedback. A modification of the writing system (thicker paper, soft support) combined with the exertion of higher pressure at resting points creates depressions in the paper. The pen tip's next entering of such a depression can be felt by proprioception in the finger-hand system, similar to a car's wheel being caught in a pothole is sensed by the driver through the car's body: the pen acts as a transmitter from paper to hand for perturbations created by this event.

5. Example: drawing of wire cubes with the letter A by using proprioception

With the solution from the last section, the usage of muscle feedback for signaling, "goal point reached", we may expect better stereograms. Fig. 4 shows the result. In the upper part, you can see a both-handedly drawn stereographical sketch of a cube in frontal view and edge view. It was produced while looking at the scene in parallel view. Here (as in Fig. 3), proprioceptive feedback has been used in addition to visual feedback. Comparing Fig. 4 shows more "hits" than Fig. 2: the A letters reach the vertices more reliably, though the right upper figure shows an overshoot of the tip of an "A" beyond the edge. In the lower part, a one-handedly drawn stereogram is shown for comparison. Here, the left side was done by the left hand, then the right side by the right hand, both under normal view. The lines to the left show irregularities. The right hand tried to imitate these for reaching a better 3D-match. (Grid paper was used between paper and soft support to allow stable parallel view, here with a dot distance of 65 mm.)

Readers might not be able to notice a considerable improvement of Fig. 4 (upper part) compared to the corresponding Fig. 2 (upper part). You might be right. The conscious proprioceptive feedback from above can only yield a confirmation of having reached a virtual 3D goal point (right and left 2D goal points). It can neither assure a smooth path between the endpoints of line segments, nor synchronous motions of the two pen tip. As in our nose-touching

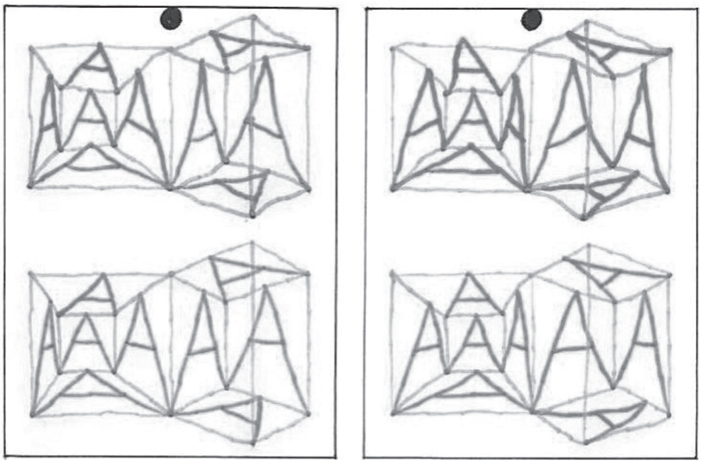

Fig. 4: Stereogram. Above: Both-handedly drawn stereographical sketch of cubes with "A"s in frontal and edge view (as in Fig. 2), now made by using also proprioceptive feedback (as in Fig. 3). Below: These cubes with "A"s have been drawn one-handedly, the left side by the left hand, then the right side by the right, both under normal view.

experiment: even if we succeed in blindly reaching our nose with both fingers, we can neither tell anything about the path the fingers took to reach it, nor whether the two fingers moved in synchrony, if we only use our sense of touch.

Because of this reason, some additional modes of visual feedback have to be used. Since proprioception from above tells only success, but not failure, there must be some decision about the continuation of the path of one pen tip, if just the other has reached its goal point. The simplest method would be to close the other eye in order to see clearly the late coming pen tip's location relative to the goal point, and then to plan and execute an appropriate motion. But this brute force method would interrupt the parallel viewing mode, an unspoken assumption of this paper. Other modes of online feedback, which are compatible with parallel view, will be explained in the discussion below.

Concerning the research question of this paper, however, we can state: Looking at Fig. 4 (upper part) reveals that now all legs of all the A letters start or end in vertices of the wire cubes, and this is a first step towards higher stereogram precision.

Summary: This section presented an example for stereo drawing and stereo writing using proprioceptive feedback in addition to visual feedback. The upper part of Fig. 4—made both-handed under parallel view—shows all legs of the letters A ending in a vertex of a wire cube. For most of the legs of the letters A, the arrival in the vertices could be felt by proprioception. However, reaching the goal points precisely is only a necessary condition for a good stereogram perceivable in 3D. This also requires matchable paths between start and goal points, a condition often violated in the upper part of Fig. 4 (drawn both-handed), better achieved in the lower part of Fig. 4 (drawn one-handed).

6. Discussion

In this section, the employed types of visual and proprioceptive feedback are treated. First, non-3D modes of vision will be discussed that have also been used for this paper's examples, an important by-product of this research. Second, I will argue for the main thesis of this paper: proprioception is important for improving the quality of manually drawn stereograms and for facilitating the visual perception of the drawing process in 3D.

Since proprioception helps only in the last milliseconds before arriving in the goal, we first look at the longer time period before: How to trigger 3D perception on the way between two points? How to reach a better synchrony of paths or similarity of corresponding lines in both-handed drawings or writing? And how can the writing/drawing process be continued, even if 3D perception fails? Some considerations:

1. The configuration of both hands and pens in combination with the viewing angle must assure the visibility of both lines being drawn and of both goal points (no occlusion!). Good light conditions seem also to be essential.
2. Whenever there is any doubt whether the line being drawn or the goal point are perceived in 3D (by fusing two perceptual entities) or just in 2D (e.g. one half image being

suppressed by our brain, or essential visual elements being occluded), the dynamic scene should be checked in 2D (current path of pen tips, relative location of both 2D goal points) in the visual field.

3. This can be done by provoking double images (diplopia[6]) of the virtual goal point or the virtual line. The goal here is to separate, to diffuse the merged goal point or pen tip, and instead to perceive their constituting pair of 2D points or pen tips, but still in the center of the visual field, and thus *still under parallel view*. A slight deliberate convergence or divergence of the eyes yields a certain horizontal disparity that produces horizontally neighbored double images, whereas a slight tilt of the head yields vertically neighbored double images (*vertical disparity*). In the following, three configurations of the essential visual elements are described:
   (i) Pen tips separated, goal point fused: The task is to create two converging line segments that meet in the single goal point simultaneously.
   (ii) Pen tips are fused, goal point is separated: The task is to create two diverging line segments that reach the two goal points simultaneously.
   (iii) Both, pen tips and goal points are separated: The task is to draw two separated lines that reach the goal points at the same time.[7]
   (iv) If the cognitive load is high, slowing down the drawing motions can help, or even temporarily resting one of the hands (possible term: *temporal disparity*). If suppression of one half image occurs, there is a tendency for the stationary image to be suppressed, and for the dynamic one to be perceived. Therefore, by swapping the writing hand and resting hand in small time intervals from right to left and back might help to swap the perceived half image from right to left and back, too.
4. If the visual field is occupied with too many lines, it might be difficult to spot the two pen tips and the two goal points or to plan a path. Gazing at the fused image in the center of the visual field might be too confusing at times. In such a case, gazing under parallel view in the periphery and observing the complementary half images can clarify the scene, since the left periphery shows only the left half of the stereogram and helps the left hand's motion planning and vice versa.

These 2D-modes of vision under parallel view may sound like cheating, since the expectation is 3D perception of the scene. However, they should be considered as alternatives, when 3D view is hampered. They can be useful for quick checks, eventually helpful for correcting a path midway and for 3D perception to resume. In the long run, their usage could support the development of continuous 3D perception.

If there are so many non-3D viewing modes under parallel view, why to use proprioceptive feedback at all? There are several reasons:

1. The different nature of proprioception gives the writer/drawer another degree of confidence for having reached a goal point: this feedback indicates it clearly, precisely in space and time.

2. Concerning spatial precision: The precision of visual feedback is not as high as proprioception here. It is like a key that is put into a lock by visual control first, but then through touch and muscle feedback, and finally sits in the lock with a precision unreachable by visual guidance alone. The lock actually guides the key mechanically into its final position. In a very similar way, a ball-shaped pen tip is guided by the walls of the depression exactly into its center.
3. Concerning temporal precision: You might have felt in the nose-touching experiment that one of your fingers was quicker, even if the time lag between both contacts might have been small. Similarly, proprioceptive feedback from both pen tips can reveal tiny time lags between the arrivals at the two goals, which may be not perceivable for the eyes. These data can be useful for motor learning in order to achieve better synchronization between the two hands.

And two final, more general arguments:

4. Using both, visual and proprioceptive sense in combination for solving the stereo writing tasks is also in accordance with the sensorimotor contingency theory (O'Regan & Alva, 2001, p. 940) that "treats vision as an exploratory activity"and that proposes that "vision is a mode of exploration of the world …" instead of being based on internal representation of the outside world.[8]
5. Human vision has not developed independently from other senses, neither phylogenetically nor ontogenetically. It has evolved in the human species and is learned in each individual in close interaction with all other senses, e.g. the auditory, the haptic and the proprioceptive sense. If this is important for the development of the visual sense for the real world, it is most likely also important for developing a visual sense for a given virtual world, the both-handed creation process of stereograms described here.

7. Conclusion

This paper was about writing or drawing with both hands simultaneously under parallel view in order to write or draw perceptionally in 3D. There was a problem in earlier drawings: Virtual 3D lines occasionally did not reach their virtual 3D goal points; often only one of the two constituting 2D paths reached the desired 2D goals. 3D perception had obviously failed for certain time intervals. This problem could partially be solved by introducing proprioceptive feedback and by using thicker paper and a soft support, such that the hands could feel clearly where (right or left) and when (earlier or later) the pen tips arrived. The arrival can be sensed by muscle feedback, when the pen tips enter small paper depressions created by the same pen tip through applying modest pressure during line drawing just a few strokes before.

The suggested concept could solve the research question of this paper, how to sense the arrival at a goal point reliably; but it is only a partial solution to the more general problem to create a good stereogram manually, since proprioception tells only *when* and *where* the goal points were reached, but not *how* to reach them. For the latter problem, different feedback is needed for time intervals without 3D perception, e.g. conscious perception of double images by deliberately produced horizontal, vertical or "temporal" disparities.

One point has become clear: Writing with both hands synchronously under parallel view does not necessarily ignite a kind of "3D perception engine"; we cannot expect to perceive and draw lines and to immediately perceive these emerging lines in 3D, and thus to draw good stereograms without training. It is rather the other way around: If we manage to solve the complex sensorimotor task to draw both-handedly good stereograms under parallel view, then we have a chance to start perceiving the writing or drawing process in 3D *if and only if this helps the job to be done*. Human beings are optimizers, and so are our sensorimotor faculties. 3D perception has not evolved for pleasing the aesthete but for survival, for sensing the environment quickly and precisely. Therefore, the primary goal must be to improve the quality of the stereogram, even by employing 2D-viewing modes, and 3D perception could possibly be the final result.

Notes

1 Transverse wave: A wave that oscillates perpendicular to the direction of its propagation (e.g. electromagnetic waves).

2 Longitudinal wave: A wave that oscillates in the direction of its propagation (e.g. sound waves).

3 The real pitch curve has discontinuities that would result in low legibility. Thus, practical PW is a compromise between the ideal PW showing the pitch contour truthfully and normal text with its usual horizontal contour.

4 „Divergenz der Augen lässt sich ebenfalls bei der Betrachtung stereoskopischer Bilder erzielen, wenn man sie immer weiter von einander entfernt und dabei ihre Vereinigung zu einem Bilde zu erhalten sucht. Ich kann auf diese Weise eine Divergenz meiner Blicklinien bis zu 8 Grad hervorbringen." (Helmholtz 1867, 475).

5 Disparity in computer-generated stereograms is often relatively small, such that a 3D scene can be seen completely in an instant (possibly after initial matching or focusing problems), whereas here, disparity is relatively big, such that the perception of a 3D scene proceeds only incrementally, portion by portion. Therefore, 3D perception of many computer-generated stereograms is easier.

6 However, this is not really physiological diplopia, a term referring to the perception of a double image from one physical object. The object being unmerged here is a virtual object, stemming from two separate physical images. "Virtual physiological diplopia" might be a better term.

7 Once more, the grid on the paper helps, since it can simplify planning and mentally visualizing intermediate points towards the goal points, and thus supports path planning.

8 This view could also pave a way for 3D perception of the stereograms with large disparity in this paper: By visually scanning the wire cubes along their edges repetitively as a mode of exploration, the 3D impression would not be born out of a visual percept at an instant, but would grow slowly from the spatio-temporally extended experience of sensorimotor activity.

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