Judging an unfamiliar object's distance from its retinal image size

Rita Sousa Research Institute MOVE, Faculty of Human Movement Sciences, VU University, Amsterdam, The Netherlands

Eli Brenner Research Institute MOVE, Faculty of Human Movement Sciences, VU University, Amsterdam, The Netherlands

Jeroen B. J. Smeets Research Institute MOVE, Faculty of Human Movement Sciences, VU University, Amsterdam, The Netherlands

How do we know how far an object is? If an object's size is known, its retinal image size can be used to judge its distance. To some extent, the retinal image size of an unfamiliar object can also be used to judge its distance, because some object sizes are more likely than others. To examine whether assumptions about object size are used to judge distance, we had subjects indicate the distance of virtual cubes in complete darkness. In separate sessions, the simulated cube size either varied slightly or considerably across presentations. Most subjects indicated a further distance when the simulated cube was smaller, showing that they used retinal image size to judge distance. The cube size that was considered to be most likely depended on the simulated cubes on previous trials. Moreover, subjects relied twice as strongly on retinal image size when the range of simulated cube sizes was small. We conclude that the variability in the perceived cube sizes on previous trials influences the range of sizes that are considered to be likely.

Keywords: depth, spatial vision, binocular vision

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Introduction

A cube could have any size at any distance, so the size of its retinal image on its own does not tell you much about its distance. If the cube is a familiar object, for instance, a dice, so that its size is known, then the retinal image size is a reliable cue for distance. However, even if the cube is not a familiar object, so you do not know its precise size, you may consider some cube sizes to be more likely than others. For instance, when have you last seen a cube with sides of about 1 m? Moreover, certain sizes are more likely than others in specific situations. If you are asked to repeatedly bring your finger to a cube, you may expect the cube to always be the same. Furthermore, if you are asked to bring your finger to the center of the cube, you will expect the size of the cube to be a few centimeters, as it would be irrelevant to specify the center for a cube of a millimeter and physically challenging to bring your finger to the center of a cube of about 1 m. Therefore, retinal image size may not only play a role when judging the distance of familiar objects (Gillam, 1995; McIntosh & Lashley, 2008; Sedgwick, 1986) but also when judging the distance of unfamiliar ones (Collett, Schwarz, & Sobel, 1991; Lugtigheid & Welchman, 2010; Sousa, Brenner, & Smeets, 2010).

If people consider the likelihood of objects having certain sizes when judging the objects' distances in the manner described above, we expect to be able to influence an object's apparent distance by changing information about likely sizes. If we repeatedly present people with objects of about the same size, they are likely to shift what they consider to be a likely size (their size prior) toward this perceived size. Here, we examine whether the confidence that people have in retinal image size as a cue for distance when judging unfamiliar cubes' positions in depth (the width of the prior) is affected by the consistency of the simulated cubes' sizes across presentations.

Participants were asked to judge cubes' distances in total darkness. We manipulated the variability in size. Within two conditions, we presented cubes of about the same size (with different sizes for the two conditions). In order to be able to estimate the role of size in judging distance, the cubes within these two conditions had to differ in size to some extent, but the difference was only 20%. In the third condition, the cubes had a large variety of sizes (they could differ by a factor 10). Our main question was whether more weight would be given to size as a cue to distance in the first two conditions, in which all cubes had about the same simulated size, because in those conditions retinal image size provides a more reliable measure of distance. We evaluated the weight given to size from the difference

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between distance judgments for slightly smaller and bigger cubes that were presented at the same position. We expected subjects to point further away for the smaller cube. The extent to which they did so indicates how much they relied on size as a cue to distance.

Methods

Subjects

There were 12 subjects. None of them knew the purpose of the experiment. Their stereo acuity was better than 80 arcsec.

Apparatus

We used a setup with mirrors that reflect the images from two CRT monitors (1096 × 686 pixels, 47.3 × 30.0 cm) to the two eyes to produce simulations of three-dimensional objects (see Figure 1). New images were created for each eye with the frequency of the refresh rate of the monitors (160 Hz). The 3D positions of the subject's head and right index finger were recorded at 250 Hz using infrared emitting diodes (IREDs) and an Optotrak 3020 System (Northern Digital).

One IRED was attached to the nail of the subject's right index finger and three others to a mouthpiece with a dental imprint. The positions of the subject's eyes relative to the mouthpiece were determined in advance. The measured position and orientation of the mouthpiece was used to adapt the images to the eyes' changing positions. This was necessary because subjects were allowed to move their head freely during the experiments (although they could not move very far since they had to look into the mirrors). The calibration procedure is described in detail elsewhere (Sousa et al., 2010).

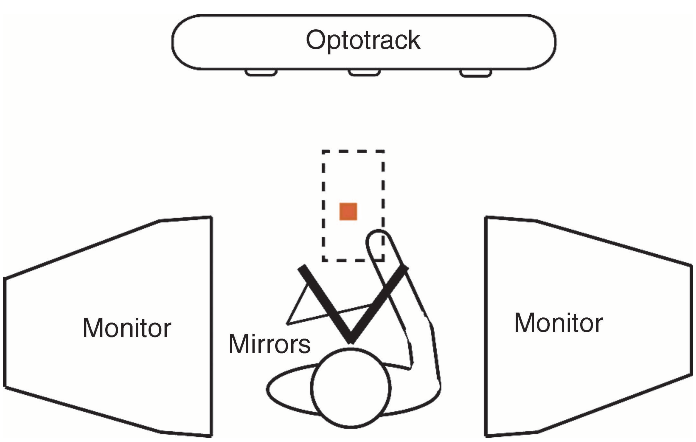

Figure 1. Top view of the setup. The dashed lines indicate the region within which the virtual stimuli were presented.

Conditions

Red cubes were presented in total darkness. Their surfaces had Lambertian reflectance with half the simulated illumination being ambient and the other half being from a distant light source above and 30 deg to the left of the subject. The cubes were positioned within a volume of space of 8 × 8 × 20 cm (height × width × depth) that was centered about 46 cm from the subject's eyes. The volume was lower than the subjects' eyes and oriented downward by about 30° so that the subjects pointed at a comfortable height while the space was elongated (depth axis) along the line of sight. All the cubes had the same orientation: Their edges were aligned with the edges of the volume of space.

Our choice for the above-mentioned volume of space meant that the range of possible heights and lateral positions in the visual field was larger for nearby cubes. However, more distant cubes were not systematically higher in the visual field or further to one side. The ocular convergence that was required to fixate the cube, the relative disparities between the edges of the cube, and motion parallax if the subject moved his or her head all provided information about the simulated distance.

In the *small sizes* condition, the cube could have one of two sizes: sides of 1.0 and 1.2 cm. In the *large sizes* condition, the simulated cube sizes were three times as large: sides of 3.0 and 3.6 cm. Cubes of all four sizes were presented at the same 60 positions. In the *mixed sizes* condition, the 240 cubes presented in the *small sizes* and *large sizes* conditions were interleaved with 60 other cubes. Of the other cubes, 20 had sides of 0.5 cm, 20 had random sizes between 2.0 and 2.5 cm, and 20 had random sizes between 4.5 and 5.0 cm (see Figure 2). The three conditions were presented in separate sessions on different days. The order of the conditions was counterbalanced across subjects. Within each condition, the sizes and positions were presented in random order.

Procedure

Subjects started each pointing movement with their hand near their body. They were instructed to move their unseen index finger to the center of the cube and to hold the finger steady to indicate where they saw the cube. The pointing movement was considered to have ended if the hand had not moved more than 1 mm in 300 ms and was within 30 cm of the center of the volume of possible cube positions. At that moment, the finger position was saved and the cube disappeared.

Analysis

The next cube only appeared after the subject had brought the hand back near the body. We determined three

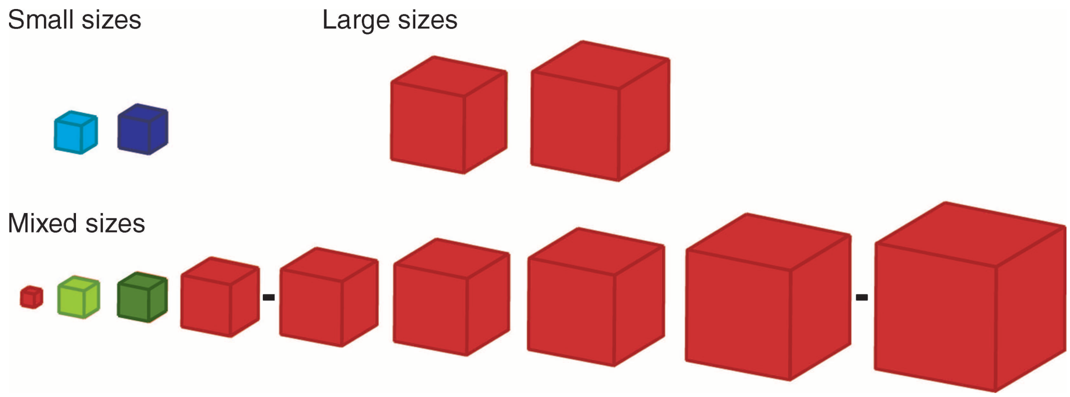

Figure 2. Schematic representation of the simulated cube sizes in the three conditions. The cubes shown in the small sizes and large sizes conditions are identical to those of the mixed sizes condition that are directly below them. The colors identify the corresponding coding in Figure 3; the simulated cubes were all the same color (red).

measures for the use of retinal image size from the pointed distances (the distances between the saved finger position and the point between the eyes). Since we presented all the relevant cubes at the same 60 positions, we could easily summarize the influence of cube size in a single value: the average difference between the pointed distance when pointing at the larger and smaller cubes. We will refer to this average difference as the "influence of cube size." We determined the *influence of cube size* separately for the matched 1.0- and 1.2-cm cubes in the *small sizes* and *mixed sizes* conditions and for the matched 3.0- and 3.6-cm cubes in the *large sizes* and *mixed sizes* conditions. For every subject, we averaged these influences for the *small sizes* and *large sizes* conditions and did so for the two sizes of the *mixed sizes* condition. We tested whether the influence of cube size was consistently smaller (indicating that the size prior is wider) in the mixed condition with a paired *t*-test.

The second measure that we used was the slope of the relation between simulated distance and pointed distance for each cube size. Since the simulation does not include all possible cues (e.g., required accommodation does not vary with simulated distance; Watt, Akeley, MO, & Banks, 2005), and there may be a bias toward a certain distance (Gogel, 1961), giving more weight to cues that change with distance in accordance with the simulation will result in the above-mentioned slope becoming steeper (for veridical pointing at the simulated distance, the slope would be 1). For a given simulated cube size (and the slopes were determined separately for each simulated size), retinal image size is a reliable cue for the object's simulated distance, so giving more weight to size as a cue for distance will result in steeper slopes. For every subject, the slopes for the four cube sizes in the *small sizes* and *large sizes* conditions were averaged, as were the slopes for the same cube sizes in the *mixed sizes* condition. We tested whether these average slopes were consistently shallower (again indicating a wider prior) in the *mixed sizes* condition with a paired *t*-test.

The last measure that we determined was similar to the first one, the influence of cube size, but determined by comparing pointing at the matched positions for 1.0- and 3.0-cm cubes, and similarly for 1.2- and 3.6-cm cubes. This means that for the *small sizes* condition and for the *large sizes* condition the measure (influence of cube size) was determined across conditions and, therefore, in different sessions. We used this third measure to find out whether the expected size differs between the sessions. We anticipate that the expected size (i.e., the mean of the prior) will be influenced by recent experience even if the confidence in the expected size (i.e., in the width of the prior) is not. Unless the expected size changes, the size effect will scale with the ratio between the sizes involved (assuming that the expected size can be considered as a straightforward prior). We evaluate such scaling for the influence of cube size for small and large differences in size. We do so both for the mixed sizes condition, where we assume that there is a single expected size, and for the other two conditions, where we predict that there will be different expected sizes. We express the above-mentioned ratio between the sizes as the difference divided by the sum, in analogy with Michelson contrast.

Results

Figure 3 shows one subject's pointing distances for cube sizes of either 1.0 cm or 1.2 cm. This subject pointed further away for smaller cubes (light lines higher than dark lines). The difference between the pointed distance for the 1.0- and 1.2-cm cubes was larger in the *small sizes* condition (blue lines and dots), where all cubes had about the same simulated size, than in the *mixed sizes* condition (green lines and dots), where there were many simulated cube sizes. The change in pointed distance with simulated distance is also larger in the *small sizes* condition than in the *mixed sizes* condition (blue lines have a steeper slope).

Figure 4A shows the influence of a 20% difference in cube size on the average pointing distances. The influence

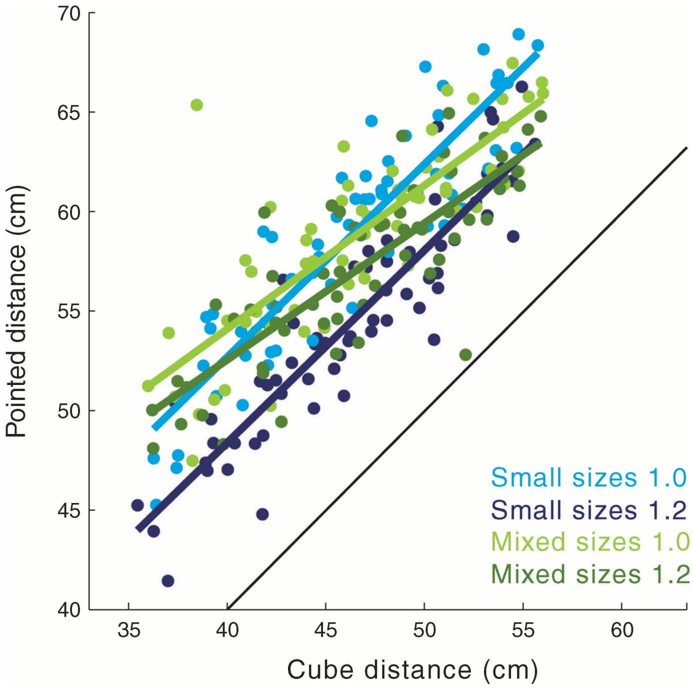

Figure 3. One subject's pointed distance as a function of simulated cube distance for cube sizes of 1.0 cm and 1.2 cm in the small sizes condition (blue symbols) and mixed sizes condition (green symbols). Each point is one response. The lines are linear fits to the points. The black line is the unity line that corresponds to veridical judgments.

of cube size in the *mixed* condition is plotted as a function of the influence of cube size in the *small* and *large* conditions. Each subject is represented by two dots: a bigger dot for the difference in pointing at the larger pair of cubes and a smaller dot for the difference in pointing at the smaller pair of cubes. The open dot represents the data shown in Figure 3. When many cube sizes were simulated (*mixed* condition), the influence of cube size was significantly smaller than it was when the simulated cube sizes never differed by more than 20% (*small* and *large* conditions; $t_{11} = 6.4$; $p < 0.001$). The difference in pointed distance halved when there were many simulated cube sizes; the best linear fit is a line with a slope of 0.49 and an intercept of -0.1 cm.

The extent to which subjects pointed further for more distant targets is larger for the *small sizes* and *large sizes* conditions than for the *mixed sizes* condition ($t_{11} = 3.3$; $p < 0.01$). This is consistent with subjects relying more on retinal image size to judge distance (for identical targets) in the *small sizes* and *large sizes* conditions than in the *mixed sizes* condition. For some subjects, the difference in slope between the conditions was larger than for others (larger deviation from the unity line in Figure 4B). Subjects for whom the average slope in the *small sizes* and *large sizes* conditions was clearly larger than the average slope in the *mixed sizes* condition tended to have large differences between these conditions in the effect of retinal image size on pointing distance (larger deviation

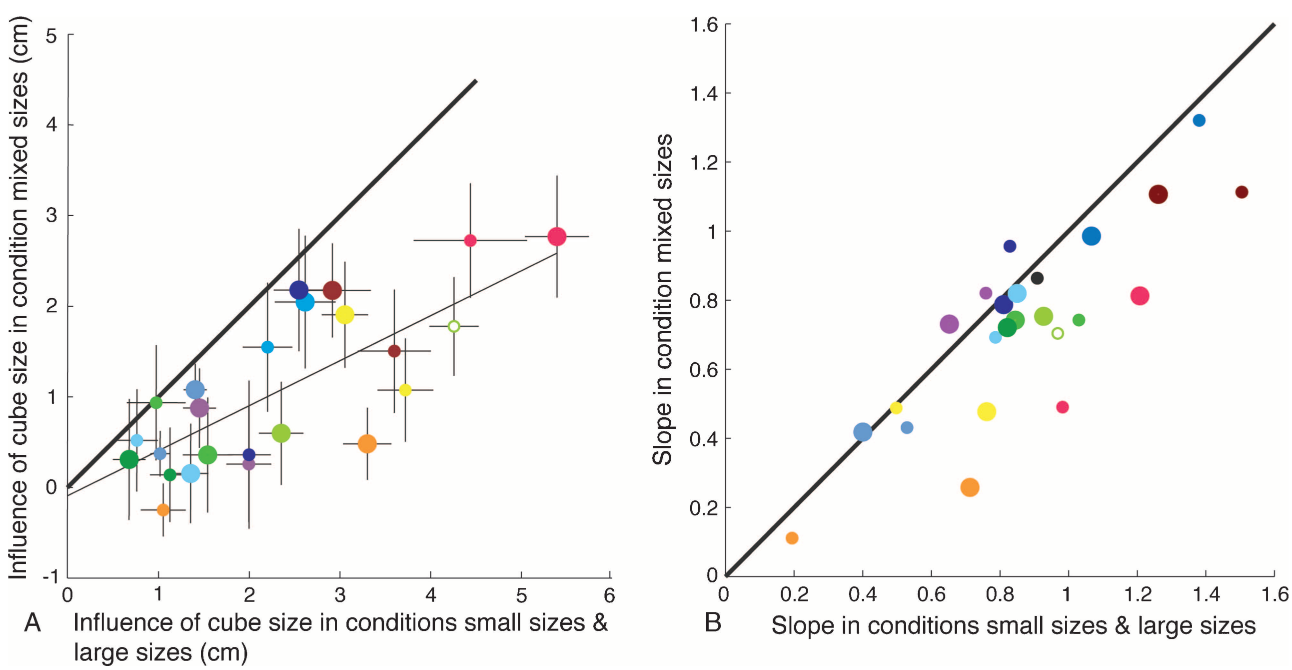

Figure 4. Two measures for the use of size as a distance cue. Values for a condition with many cube sizes as a function of values in conditions with little variation in cube size. Each of the 12 subjects' values is indicated by the same color in both panels. Data for the small and large cubes are represented by small and large dots, respectively. The small open dot represents the data shown in Figure 3. (A) Effect of a 20% difference in cube size on pointing distance, with standard errors. Note that all points fall below the (thick) unity line. The thin line is a linear fit to the data. (B) Average of the slopes of pointing distance as a function of simulated cube distance for the two cube sizes that differ by 20%. Most points fall below the unity line.

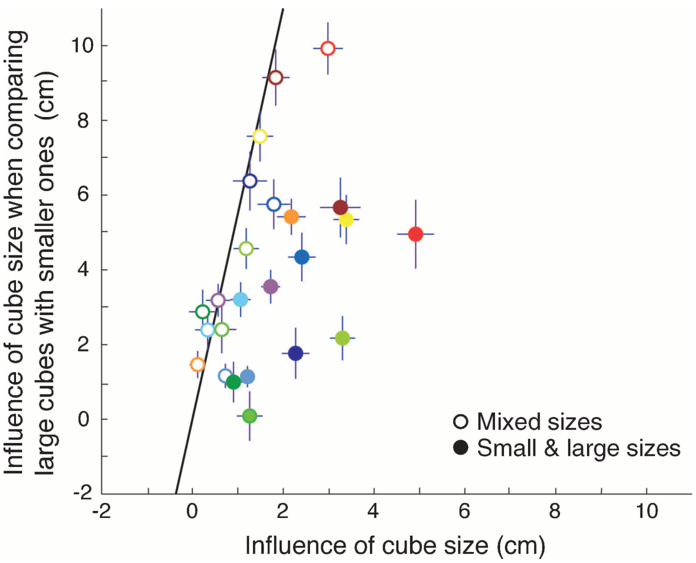

Figure 5. Effect of a threefold difference in size between the cubes (1.0 and 3.0 cm; 1.2 and 3.6 cm) as a function of the effect of a 20% difference in cube size (same data as in Figure 4A but averaged across the small and large cubes). The open dots show the effects in the mixed sizes condition and the full dots show the effects in the small sizes and large sizes conditions. The bars are standard errors. The line indicates where the values will be found if the same size prior is used for both comparisons.

from the unity line in Figure 4A). The correlation across subjects between these two measures of the weight given to retinal image size as a cue to distance was 0.69.

Figure 5 compares the *influence of cube size* when the difference in size was small (20%; always within conditions) with the *influence of cube size* when the difference in size was large (determined across conditions when considering the *small sizes* and *large sizes* conditions). In all cases, the influence of cube size was determined for matched positions. If subjects use the same prior (the same size expectation, assigned the same weight), the two measures of size effect should only differ to the extent that the size ratio differs (line with a slope of 5.5). For the *mixed sizes* condition, the points are close to the line, indicating that subjects use the same size prior for all cubes. This is not true for the *small sizes* and *large sizes* conditions, presumably because subjects learn to expect different sizes for the cubes in the *large sizes* condition than in the *small sizes* condition (which reduces the influence of retinal image size when comparing across sessions).

Discussion

Our results confirm that retinal image size is used to judge cubes' distances, even if their true size cannot be known. This implies that people expect certain objects (in our case red cubes) to be chosen from a limited range of sizes in a given situation. We used cubes, but we expect similar effects for any unfamiliar object. We found that retinal image size has a stronger influence on the judged distance when cubes have a similar simulated size on successive trials than when the simulated size clearly varied across trials. This can be explained in terms of adjustments to the *object size prior*. Consistency in the perceived cube size increases the confidence in the judgment of the cube's distance from its retinal image size and therefore decreases the width (increases the height) of the *object size prior*.

We can estimate the weight given to retinal size from the data in Figure 4A. If subjects had only relied on size to judge distance (100% weight), the 20% larger simulated cube size at the distance of approximately 46 cm would have made subjects point about 9.2 cm further away. On average, the 20% larger simulated cube size made subjects point 2.3 cm further away in the *small sizes* and *large sizes* conditions, which corresponds to a weight of 25% being given to retinal image size. The average weight was reduced to 12% in the *mixed sizes* condition.

Figure 5 shows that—as expected—experience does not only influence the confidence in judgments of the cube's distance from its retinal image size but also influences the judgment itself (by influencing what is considered to be the most likely size: the value at which the prior has its peak), as demonstrated for the comparisons involving the *small sizes* and *large sizes* conditions (solid symbols in Figure 5). Since size was not the only distance cue, the set of presented sizes became clearer during each session, and this affected further judgments within that session.

Retinal size is only an informative cue for an object's distance if one has some knowledge about that object's size. In a similar way, retinal shape is only informative about an object's slant if one knows the object's shape. Analogous to the size prior that made retinal size a useful cue for judging the distance of unfamiliar objects in our experiment, a shape prior (e.g., considering it to be likely that objects are isotropic, as are circles and squares) makes retinal shape a useful cue for judging slant. The width of this prior can also be changed by experience: One can decrease the weight given to the retinal shape cue in slant judgements by frequently presenting anisotropic target objects (Seydell, Knill, & Trommershäuser, 2010) but not by presenting anisotropic objects in the target's surrounding (Muller, Brenner, & Smeets, 2009).

Relying on an estimate of the prior probability for size is somewhat similar to relying on an estimate of the prior probability for distance, which is a way of describing the well-known "specific distance tendency" (Gogel, 1961). However, an important difference is that we propose an indirect effect, whereby the prior probability for size influences the perceived value of a different property, distance, rather than (or as well as) that of the perceived size. A prior probability for distance will presumably also influence the perceived size, because the perceived distance is used to judge the size (Brenner & van Damme, 1999), and will thereby presumably indirectly influence the size prior, but we have no direct support for this from our data. Both assumptions about likely sizes and assumptions about likely distances contribute to judgments of perceived distance (Collett et al., 1991; Gogel & Da Silva, 1987; Predebon, 1994; Sousa et al., 2010; Sousa, Brenner, & Smeets, 2011). We show that the range of experienced sizes influences not only the mean of the size prior but also the weight given to the retinal size information, and thereby distance judgments.

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Corresponding author: Rita Sousa.
Email: ritass@gmail.com.
Address: Van Der Boechorstraat 9, Amsterdam 1081BT, The Netherlands.

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