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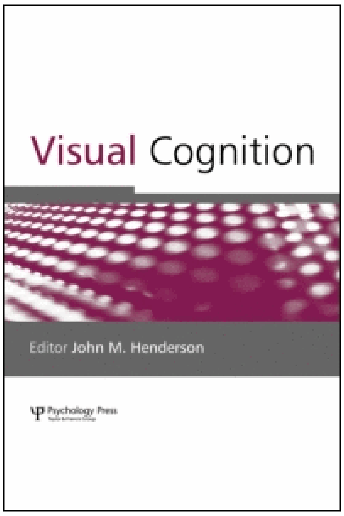

Visual Cognition
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713683696

Categorical perception of morphed objects using a free-naming experiment

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First published on: 09 July 2010

To cite this Article Hartendorp, Mijke O. , Van der Stigchel, Stefan , Burnett, Hollie G. , Jellema, Tjeerd , Eilers, Paul H. C. and Postma, Albert(2010) 'Categorical perception of morphed objects using a free-naming experiment', Visual Cognition, 18: 9, 1320 — 1347, First published on: 09 July 2010 (iFirst)

To link to this Article: DOI: 10.1080/13506285.2010.482774

URL: http://dx.doi.org/10.1080/13506285.2010.482774

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VISUAL COGNITION, 2010, 18 (9), 1320–1347

Psychology Press
Taylor & Francis Group

Categorical perception of morphed objects using a free-naming experiment

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Morphed figures entail a dominant and nondominant interpretation. Testing perception of morphed objects using forced-choice methods demonstrates that morphed figures are perceived as their dominant interpretation ("categorical perception", or CP). Using a more natural free-naming response could reveal whether CP is an effect independent of method. In Experiment 1, therefore, series of morphed figures were tested for CP using free naming. Half of the morph series were identified as CP patterns. In Experiment 2, we used forced choice to investigate CP, resulting in an increase of number of CP series compared to free naming. The overlap between CP series of Experiments 1 and 2 was small, however. Experiment 3 revealed that higher perceptual similarity between the extremes of the series was strongly related to CP for the free-naming method, in contrast to the forced-choice method. We conclude that the observation of CP depends on the intactness of the intrinsic object structure caused by the morphing procedure.

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This work was supported by the Unconscious Boundaries of Mind project of the European Science Foundation. We thank Jeanette Mostert and Sander Bosch for their help to set up the experiment and to run participants, and Katinka van der Kooij for her help in the analyses.

http://www.psypress.com/viscog DOI: 10.1080/13506285.2010.482774

Keywords: Object categorization; Categorical perception; Free naming.

Assigning the entities in our perceptual world to discrete categories enables us to deal effectively with the wealth of information around us. One consequence of perceiving the world in categories is that the gradual merging of one entity into another will be experienced as one discrete percept abruptly switching into the other percept when crossing the category boundary. This phenomenon is known as categorical perception (CP; Harnad, 2003). Studies on phoneme perception (Liberman, Harris, Hoffman, & Griffith, 1957; Liebenthal, Binder, Spitzer, Possing, & Medler, 2005) and colour perception (Bornstein, 1987; Bornstein & Korda, 1984) have shown that a gradual change from one stimulus into another is indeed not perceived in a continuous fashion, but as an abrupt switch from one percept to the other. For instance, gradually changing the stop consonant *ba* into *da* along a continuum leads to almost 100% *ba* or 100% *da* responses. In other words, what listeners hear seems to change quite abruptly from *ba* into *da* at the moment the merged sound crosses the border of the two categories (Fitch, Miller, & Tallal, 1997).

So far, CP has been mainly examined for elementary features such as tones and colours. This might suggest that CP is primarily due to biological predispositions, because these features are present from birth (Eimas, Siqueland, Jusczyk, & Vigorito, 1971; Franklin, Clifford, Williamson, & Davies, 2005). Interestingly, the study of CP has more recently been extended from single feature dimensions towards higher order structures, such as faces and facial expressions (Calder, Young, Perrett, Etcoff, & Rowland, 1996; Etcoff & Magee, 1992; McCullough & Emmorey, 2009). For instance, a study on face recognition of famous people (e.g., gradually interpolating Kennedy into Clinton; Beale & Keil, 1995) showed patterns of CP. In line with this, several authors have argued that learned categories can be perceived categorically as well (cf. Goldstone, 1994; Harnad, 1987; Livingston, Andrews, & Harnad, 1998; Newell & Bülthoff, 2002; Verstijnen & Wagemans, 2004).

Newell and Bülthoff (2002) showed CP for familiar objects using a forced-choice paradigm. The stimuli in their study were instances of the same object category (i.e., within-category series), such as *wine bottle* and *coke bottle*, and instances of different object categories (i.e., between-category series), such as *bottle* and *lamp*. Changing each concrete object into another concrete object by small steps of equal interpolation distances resulted in a series of continuously morphed figures. Consequently, all morphed figures contained information of the two categories, with one category always more dominantly present, except for the middle figure of the morph series in which both categories were equally strongly present. Interestingly, Newell and Bülthoff observed a pattern of CP for all within-category series, and for half of the between-category series. In a subsequent experiment comparing the extremes of each morph series on shape, Newell and Bülthoff obtained a positive correlation between shape similarity ratings and degree of CP. They therefore argued that our perceptual recognition system uses CP as a mechanism to distinguish between perceptually similar objects by attending to small differences at the shape level. Hence, within-category series show a stronger pattern of CP than between-category series, because perceptual similarity is generally higher for within-category than for between-category objects (Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976).

However, the method Newell and Bülthoff (2002) used in their experiments could have more or less artificially induced the mechanism of CP. The morphed figures were tested by conducting a discrimination-identification task, a well-known method to examine CP (Macmillan, Kaplan, & Creelman, 1977). First, the discrimination task was an ABX task, in which figure X (i.e., one of the morphed figures along a continuum), identical to either figure A or B, had to be discriminated as figure A or B, being two figures along the same morph continuum. Second, in the identification task, all morphed figures had to be identified individually as one of the two extremes of the morph series. As Newell and Bülthoff acknowledged, it is possible that not one of the two extremes, but another category, was actually perceived, which could not be reported because of the two-alternative forced-choice response paradigm. Most importantly, participants were forced to choose, even when neither of the two categories is recognized in an absolute sense; in such cases, the best strategy seems to choose the most dominant one.

In light of the foregoing, the goal of the current study was to examine to what extent CP of objects also occurs with free naming or rather should be regarded more as an artefact of the forced-choice method. In the discrimination-identification task (Newell & Bülthoff, 2002), the dominant and nondominant categories (i.e., the extremes of a morph series) were known to the participants. However, in a free-naming task these interpretations are unknown to the participants. As such, in a free-naming situation arguably more continuous interpretation of mixed stimuli is possible. Hence, showing categorical perception even under these circumstances would have a major theoretical impact on how our visual system deals with ambiguous information.

Free naming could result in one of three response patterns. First, the morphing percentages could directly be reflected in the interpretation patterns, a so-called *pattern of morphing*. In other words, a morphed figure based on 70% of extreme A and 30% of extreme B will be interpreted by 70% of the observers as extreme A and by 30% as extreme B. All category information available in the morphed figure will bear on what observers perceive. Second, the morphed figures could always be perceived as the dominant category (i.e., as the extreme object of which more than 50% was present in the morph): A clear *pattern of CP* should appear. Third, no recognition of either of the two extremes is possible for those figures in which the difference between the dominant and the nondominant category is relatively low (i.e., 70%30% and 60%40%). Hence, when freely naming these figures observers may generate a great variety of names without a clear pattern (i.e., *no distinct pattern*).

In Experiment 1, the morphed figures were tested for CP using a free-naming method. Each morphed figure was presented individually in random order, and participants were asked to give their interpretation of the object with no restrictions to naming. In Experiment 2, the same morphed figures were tested for CP, but then using a forced-choice method. A comparison between the findings of Experiment 1 and 2 could reveal to what extent this perceptual mechanism is influenced by the method of testing and to what extent CP is a phenomenon applied to the perception of concrete objects. The design of these two experiments was kept similar as much as possible to enable this comparison. If CP is affected by the method of forced-choice, a greater number of series showing CP is expected in Experiment 2 than in Experiment 1. In Experiment 3, we examined the reasons why some series of morphed figures show CP whereas others do not. We looked more closely at different aspects of (visuospatial) perceptual similarity and of general semantic similarity. Moreover, the stimulus material consisted solely of between-category objects for which perceptual similarity might play a different role than for within-category objects.

DEFINING CATEGORICAL PERCEPTION

To test morphed objects for CP using a free-naming method, a new set of criteria of CP was necessary. Based on criteria described in earlier studies on CP (Calder et al., 1996; Harnad, 1987), we defined a CP data pattern as a pattern in which each morphed figure along a continuum is interpreted as its dominant interpretation, except for the 50%50% figure for which both interpretations might be given. However, when the nondominant interpretation influenced the interpretation of a morphed figure, a pattern of morphing resulted. This means that the morphing percentage was reflected in the answer pattern; thus, a 70%30% morphed figure would be interpreted by 70% of the observers as the dominant interpretation and by 30% as the nondominant interpretation. The four basic response patterns we discriminated are schematically shown in Figure 1.

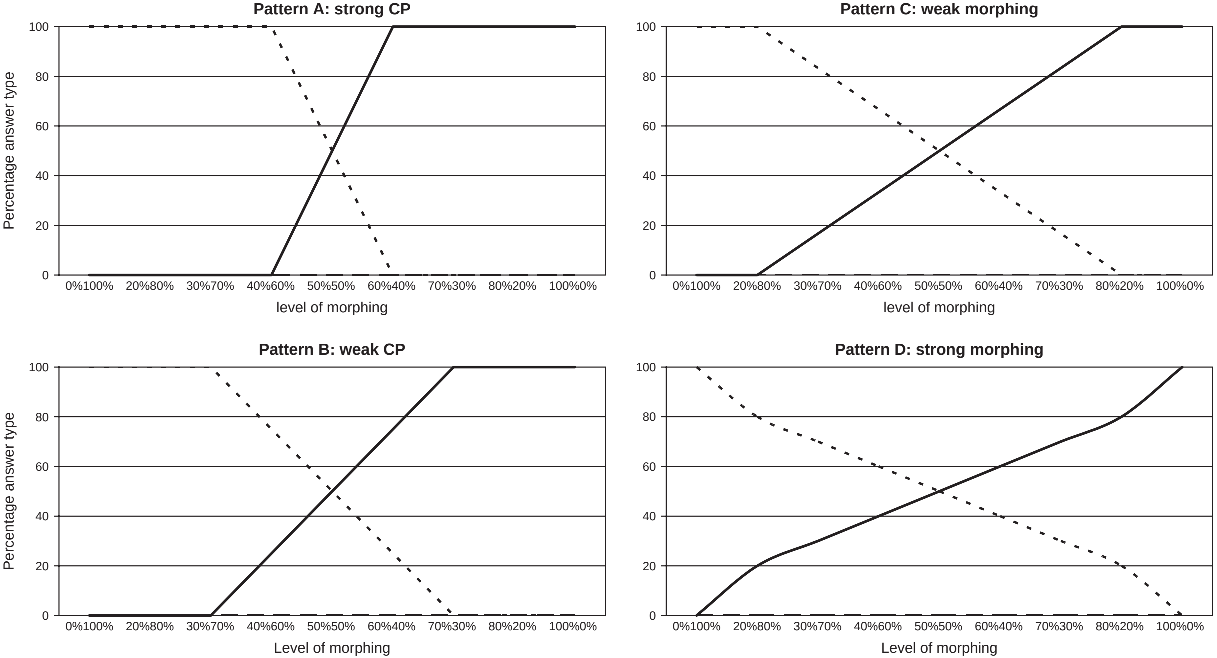

Figure 1. Patterns A–D. The x-axis refers to the levels of morphing, the y-axis to the percentage of responses a certain answer type was shown by the data pattern. The dotted line refers to one extreme; the closed line refers to the other extreme. The dashed line corresponding to the alternative answers is presented for all levels of morphing at a response level of zero.

First, Pattern A reflects *strong categorical perception*. The switch from one interpretation to the other interpretation is between 40%60% to 60%40% for one interpretation (extreme B) and for the other interpretation (extreme A) between 60%40% to 40%60%. Both lines cross one another at 50%50% at a 50% answer level, meaning that 50% of the answers is similar to extreme A and 50% is similar to extreme B. The line for the alternative answers is for all four basic patterns at an answer level of zero at each morphing level. Second, Pattern B of *weak categorical perception* shows a similar pattern to Pattern A, except that the switch moment is shifted from 40%60% to 30%70%. Third, for Pattern C of *weak morphing* all features of the data pattern are similar to the previous two basic patterns, except that the moment of switching is shifted to 20%80%. Last, in the *strong morphing* Pattern D, the answer percentages reflect the levels of morphing as described previously (e.g., a 70%30% figure is perceived by 70% of the observers as the dominant interpretation and by 30% as the nondominant one). Patterns A and D were based on an ideal response pattern, which might be found under conditions of forced-choice, but would be highly unlikely under free-response circumstances, because other interpretations besides the dominant and nondominant ones would disrupt it. We could not predict a pattern for the alternative answers because previous studies used forced-choice methods. Therefore, this line was kept at a percentage level of zero. In addition, the moment of switching from one interpretation to the other need not necessarily be the same for each participant. We tried to reduce these individual differences by testing a great number of participants, but this still could affect the moment of switching for a morph series. Therefore, we introduced Patterns B and C, which captured a greater area in which the moment of switching could happen.

EXPERIMENT 1

Method

Participants. A total of 83 students from Utrecht University and University College Utrecht participated in this experiment. All were fluent in Dutch. They received a fee for participating. The experiment lasted about 10 minutes.

Materials. Suitable objects were selected from a large set of contour drawings of a wide range of living and nonliving objects for which normative identification rates had been established (de Winter & Wagemans, 2004), which in turn were based on the standard set of line drawings by Snodgrass and Vanderwart (1980). In addition, the figure of a man was selected from another stimulus set (Downing, Bray, Rogers, & Childs, 2004).

Morphs (i.e., interpolations) between pairs of objects were made using Sqirlz-Morph software (Xiberpix, version 2.0). In this program, markers were positioned on salient locations of each shape contour, with the same number of markers for the two shapes that would be morphed. The morphing procedure produced linear interpolations between corresponding markers on the two shapes. The interpolation between the markers on a contour shape was decided by (bending) energy minimization (metaphorically the deforming of a thin metal plate). Morphs were made between two living objects (2 pairs out of 15 morph series), two nonliving objects (3 pairs out of 15 morph series) and between living and nonliving objects (10 pairs out of 15 morph series) (Mehta, Newcombe, & de Haan, 1992). Each morph series consisted of 19 interpolations (5% change). From each complete morph series nine figures were selected: The two extremes (0%100% and 100%0% figures) and the 80%20%, 70%30%, 60%40%, 50%50%, 40%60%, 30%70%, and 20%80% figures. In total, 15 different series were used. Seven out of the 19 interpolations from each series were used to reduce exposure to the same series as much as possible (see Figure 2 for a complete overview).

Furthermore, all paired extremes were from different (basic-level) categories and most of them from different superordinate categories (Rosch et al., 1976), such as the morph series *Duck-Church*, which are members of the superordinate categories *animal* and *building*, respectively. The majority of the objects were seen from profile view; a minority faced forwards (Bernstein & Cooper, 1997). A regular keyboard was used to enter the free-naming responses. The experiment was programmed in Direct RT (Empirisoft, 2006).

Procedure. The experiment consisted of 135 trials (9 figures per morph series × 15 morph series). These were presented randomly, with the restriction that figures of the same series were presented so that they were separated by at least seven items of different series. This randomization was introduced to reduce a learning effect by previously presented figures of the same series. Each figure was presented only once.

At the start of the experiment, participants were instructed to name each target by free response, which meant they were free to give any answer as long as it was an interpretation of the figure. Three types of answers were possible: Answers corresponding to (1) the dominant interpretation, (2) the nondominant interpretation, or (3) answers that fitted neither of these (i.e., the alternative answers). Some restrictions were included to prevent too diverging responses, such as answers should exist of one word, and could not be diminutives (e.g., *small shoe*), subordinates (e.g., *sport shoe*), or the name of a brand (e.g., *Nike*).

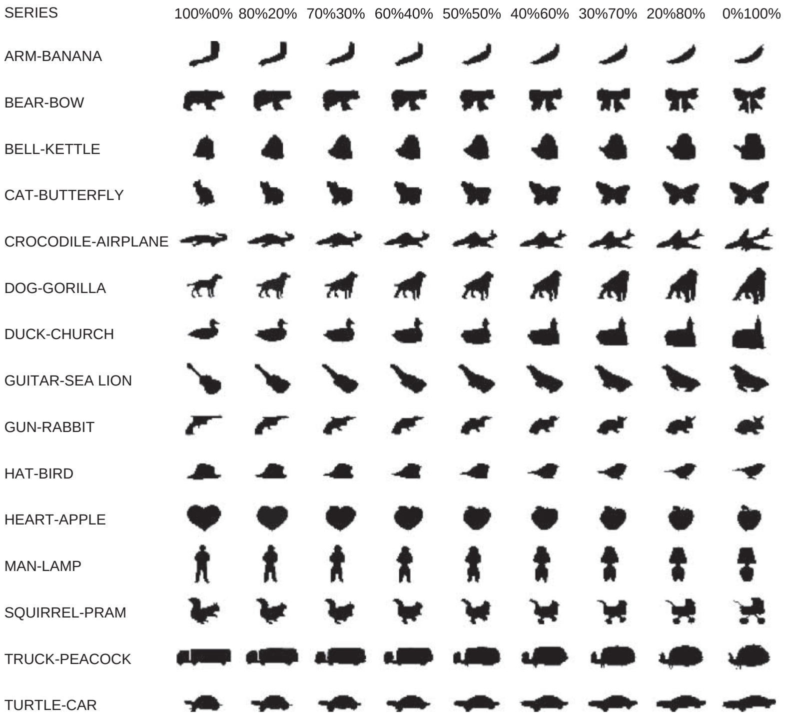

Figure 2. The 15 morph series tested in Experiments 1 and 2. Each morph series includes nine items, namely 100%0%, 80%20%, 70%30%, 60%40%, 50%50%, 40%60%, 30%70%, 20%80%, and 0%100% figures.

Participants were given three practice trials, showing 100% figures which were not part of the experimental series, which followed the same procedure as the experimental trials. First, a fixation cross was presented in the middle of the computer screen for 750 ms, followed by the question "what do you see here?" (in Dutch). Simultaneously, a target (i.e., one of the nine figures from one of the 15 morph series) was presented on the screen. Participants were instructed to type their interpretation of the target by using a keyboard placed in front of them. They could view what they were typing at the bottom of the screen (i.e., below the target), and could correct typing errors by using the backspace button. There were no time restrictions to ensure that no missing data would be collected. Trials were separated by a blank screen, the duration of which was determined by the participant by a spacebar press.

Data analysis. The data matrix was organized by horizontally presenting all targets and vertically presenting all participants. Responses were scored as 0 for one extreme (e.g., *duck* to a target of the *Duck-Church series*), as 1 for the other extreme (e.g., *church* to a target of the *Duck-Church series*), or a score of 2 for alternative answers (e.g., *chimney* or *basket* to a target of the *Duck-Church series*). Nevertheless, reexamination of all alternative responses shifted some responses from the alternative category to one of the extreme categories, because they were a synonym or closely related (semantically or based on appearance) to the dominant or nondominant interpretation, such as *goose* in the *Duck-Church* series. This data matrix was analysed for frequency percentages of answer types per series. The graph of these frequency percentages presented the response patterns for each series separately. These graphs were compared to the graphs of the CP and morphing data patterns described in the introduction.

It was likely that due to individual differences the data pattern for each morph series would not show such a straightforward pattern as the data patterns of Patterns A–D with an abrupt switch from one percept to another or a strong linear decrease of one of the percepts. These limitations could be dealt with by a statistical model, namely the Birmbaum model, which we used to examine CP. In the next subsection, Statistical Model, a description of this model will be outlined. Based on this model, the steepness and the moment of switching from one percept to another could be measured. By comparing the values of the four data patterns of CP and morphing to the values of the data patterns of the morph series, series could be identified as showing one of the three patterns, namely a CP pattern, a pattern of morphing, or no distinct pattern.

Statistical model. In the following we refer to the two extreme images as image A and B. When the morphing level is 0% (100%), the pure image A (B) is shown. We assume to model the probability of choosing image B.

A proper model should allow a gradual change and have a parameter for the steepness of the curve in the region of change. The logistic curve is such a model. If $p(0 < p < 1)$ is the probability of choosing image B, and x is the morphing ratio $(0 \leq x \leq 1)$, the model is:

$$\log \frac{p}{1-p} = \alpha(x - \beta)$$

An alternative expression for the same function is:

$$p(x) = \frac{1}{1 + \exp[-\alpha(x - \beta)]}.$$

The parameter α, which we call the slope, determines the steepness of the curve, while β gives the morphing level for which $p = .5$. The latter will be referred to as X50, measuring at which moment at the continuum the switch from one percept to another takes place.

The logistic model might be applicable if the participants had to make a forced choice between the two morphed objects. That is not the case for all experiments in the current study: Sometimes other descriptions are given. We have to allow for different responses than the dominant and non-dominant response. These errors (i.e., alternative responses) are accounted for by Birmbaum's (1968) extension of the logistic model:

$$p(x) = \gamma + (1 - \gamma - \delta)\frac{1}{1 + \exp[-\alpha(x - \beta)]}.$$

Here $\gamma(\delta)$ is the expected fraction of errors made at $x = 0 (x = 1)$. As γ and δ are probabilities, their values have to be between 0 and 1. Figure 3 shows two examples of the Birmbaum model. It allows S-shaped curves with a variety of ranges, slopes, and midpoints. As our results show, this model can give a good fit to our data.

To estimate the four parameters, the maximum likelihood method has been used. Let the observations be n triples $(x_\mathrm{i}, t_\mathrm{i}\ y_\mathrm{i})$ with x_i the ith morphing level, y_i the number of subjects choosing the 100% image and t_i the size of the sample. The likelihood is proportional to $\prod p(x_i)^{y_i}[1 - p(x_i)]^{t_i - y_i}$ and its logarithm is $L = y_i\ \log p(x_i) + (t_i - y_i)\log[1 - p(x_i)]$. Given the data, L is a function of the four parameters α, β, γ, and δ, and we have to find values for them that maximize the log-likelihood.

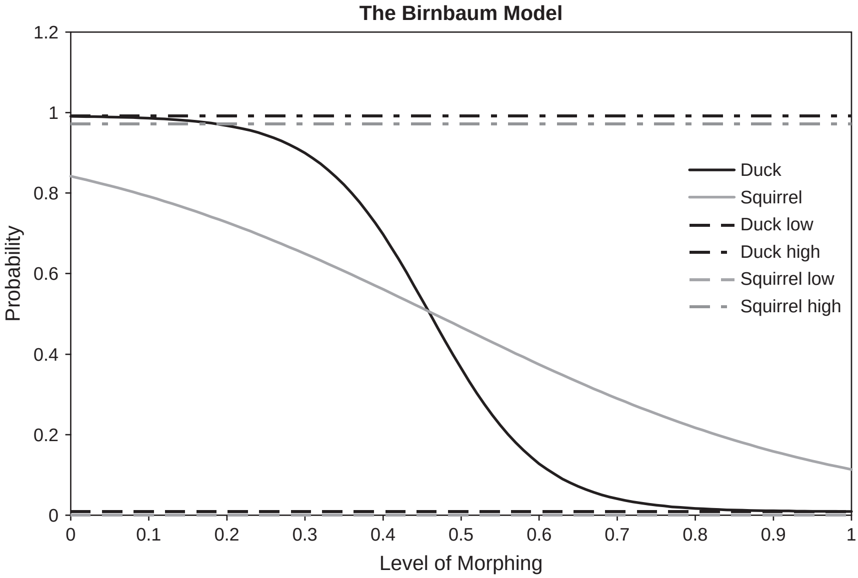

Figure 3. The logistic regression based on the Birmbaum model of the interpretation *Duck* (Duck-Church; black) and *Squirrel* (Squirrel-Pram; grey).

Estimating parameters for the Birmbaum model by maximum likelihood can only be done by numerical optimization. We could not find easily accessible software for this task, so we developed a specialized spreadsheet for Microsoft Excel. One of the so-called add-ons for Excel is the Solver. It is a powerful routine for (constrained) numerical optimization. In our experience this is a reliable and robust solution, if reasonable starting estimates for the parameters are provided. These are easily found. Our default set is $\alpha = 10$, $\beta = .5$, and $\gamma = \delta = 0$.

One of the parameters, the slope α, lacks the clear intuitive meaning of the other three. To express it in more familiar terms, we compute the "gap", $G = 4(1 - \gamma - \delta)/\alpha$. The gap is a measure to calculate the abruptness of the switch from one percept to the other. This formula follows from the following geometric construction (see also Figure 4). The tangent line to the curve at the midpoint β is constructed (it has slope $\alpha/4$). This line is intersected with horizontal lines at levels γ and $1 - \delta$. The intersections occur at morphing ratios x' (left) and x'' (right). The distance between them is the *gap*: $G = x''$-x'.

Data patterns. Due to alternative responses and individual differences, an ideal pattern of CP (Pattern A, strong CP) might not be observed, but if G is small enough it is possible to speak of an approximation of CP. This

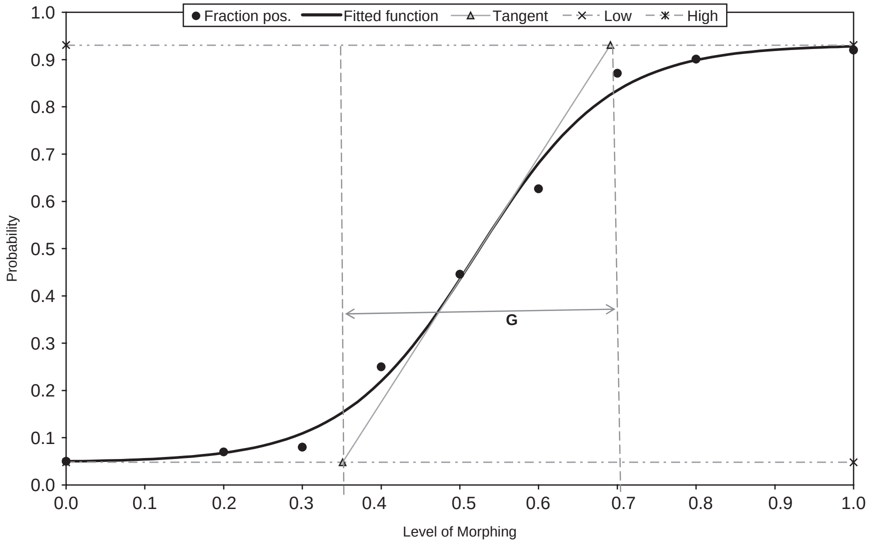

Figure 4. From the model parameters we compute what we call the "gap". It is indicated by an arrow, marked G, in the figure. The tangent line to the curve is extended to the point where it crosses the 0% level; this defines the left end of the gap. Similarly, the point where the tangent line crosses the 100% level defines the right end of the gap.

means that the observed G of the data pattern of one interpretation (either A or B) of a morph series should be similar or in-between the observed G for Pattern A of strong CP and Pattern B of weak CP (i.e., $0{,}04 \leq G \leq 0{,}24$). In addition, the X50 should be as close as possible to 0,50 (i.e., at the middle of the continuum), but at least in-between 0,40 and 0,60 (i.e., $0{,}40 < X50 < 0{,}60$). Furthermore, a data pattern could also fit the basic patterns of morphing, meaning that G should fit or be in-between the G of Pattern C of weak morphing and Pattern D of strong morphing (i.e., $0{,}39 \leq G \leq 0{,}71$). Again, X50 should be near to the midpoint (i.e., $0{,}40 < X50 < 0{,}60$). Both interpretations of a morph series should fit both assumptions of either the CP patterns or morphing patterns to be identified as patterns of CP or morphing respectively. If one or both of the interpretations of a morph series did not fit these restrictions, a series was labelled as no distinct pattern.

Results

Tables were created for each individual target (i.e., 135 tables) showing the percentages for the three types of answers. Next, the answer types were presented in a graph; each graph included three lines representing the percentage an answer type was chosen for all nine targets in a morph series (i.e., 0%100%, 20%80%, 30%70%, 40%60%, 50%50%, 60%40%, 70%30%, 80%20%, and 100%0% figures). Such a graph was created for all 15 morph series (see Figure 5 for the graphs of four series representative for the dataset).

Based on these graphs, the Gap and X50 were calculated for each series separately using the Birmbaum model. These values were matched to the Delta Gap and X50 values of the basic patterns of CP and morphing to see which series showed a CP pattern, a pattern of morphing or no distinct pattern. In Table 1, the Gap and X50 values of all series are presented, including the variance measure representing the goodness-of-fit of the estimated curve to the observed data. Here, this measure of fit is the *deviance*. It is defined as twice the difference between the "saturated log-likelihood" and the model log-likelihood. The saturated log-likelihood is obtained if the observed fractions are filled in for the binomial log-likelihood, instead of the probabilities obtained from the model.

In conclusion, based on our definitions of CP seven morph series out of fifteen were regarded as categorically perceived. These were the series *Truck-Peacock*, *Duck-Church*, *Guitar-Sea Lion*, *Heart-Apple*, *Turtle-Car*, *Crocodile-Airplane*, and *Dog-Gorilla*, presented in order of strong CP to weak CP. The remaining eight morph series, *Squirrel-Pram*, *Bear-Bow*, *Gun-Rabbit*, *Cat-Butterfly*, *Man-Lamp*, *Bell-Kettle*, *Hat-Bird*, and *Arm-Banana*,

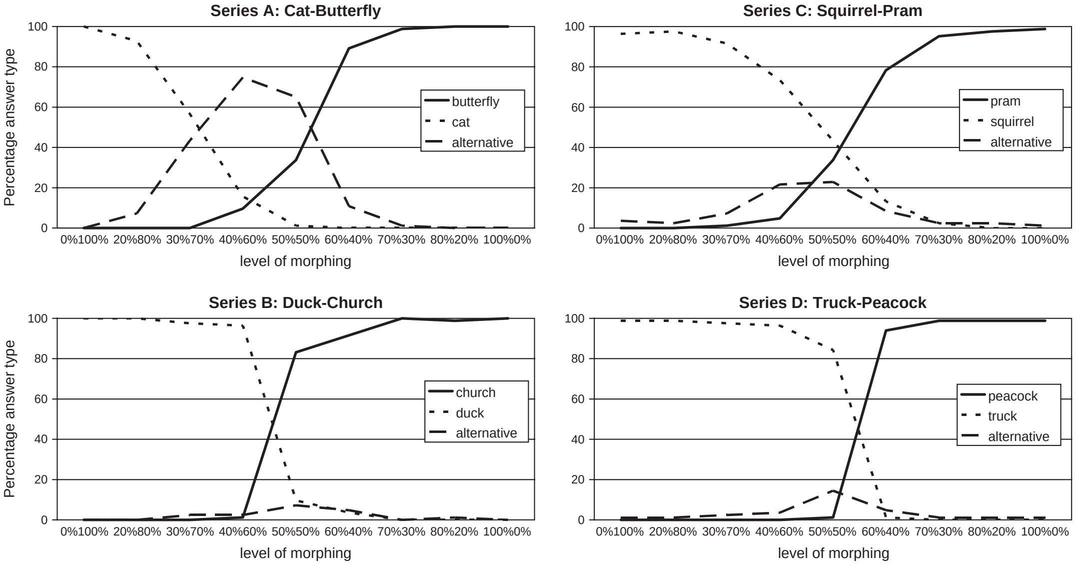

Figure 5. Four examples of data patterns of morph series. The nine levels of morphing are presented on the x-axis, the percentage that a certain answer was given is presented on the y-axis going from 0% to 100% of all responses. The dotted lines refer to the first category name of the series name (e.g., Duck for Duck-Church), the closed lines to the second category name of the series name (e.g., Church for Duck-Church), and the dashed lines to the alternative answers. Morph series B (Duck-Church) and D (Truck-Peacock) were labelled as CP, and series A (Cat-Butterfly) and C (Squirrel-Pram) were labelled as no distinct pattern.

TABLE 1
Separate presentation of Delta Gap and X50 values for both interpretations of all morph series obtained in Experiment 1

Series	*Delta Gap1*	*X50_1*	*Delta Gap2*	*X50_2*	*Deviance_1*	*Deviance_2*
Arm-Banana	0,46	0,53	0,32	0,67	24,1	8,8
Bear-**Bow**	0,22	0,40	0,22	0,48	17,7	13,8
Bell-Kettle	0,16	0,51	0,32	0,73	5,4	14,1
Cat-**Butterfly**	0,18	0,32	0,17	0,52	1,1	4,6
Crocodile-Airplane	0,23	0,44	0,21	0,51	29,8	9,8
Dog-Gorilla	0,21	0,42	0,22	0,42	6,3	7,3
Duck-Church	0,07	0,46	0,07	0,47	12,6	18,4
Guitar-Sea Lion	0,12	0,52	0,08	0,54	9,0	3,2
Gun-Rabbit	0,22	0,46	0,20	0,69	15,1	13,3
Hat-Bird	0,35	0,45	0,41	0,58	15,3	8,2
Heart-Apple	0,17	0,43	0,19	0,47	36,5	26,5
Man-Lamp	0,36	0,52	0,27	0,59	3,2	8,1
Squirrel-**Pram**	0,25	0,48	0,19	0,54	2,3	0,7
Truck-Peacock	0,06	0,53	0,05	0,56	1,5	0,0
Turtle-Car	0,18	0,56	0,18	0,56	6,4	6,4

Delta Gap1 and X50_1 refer to the first series name (e.g., Delta Gap1 for Truck-Peacock refers to Truck) and Delta Gap2 and X50_2 refer to the second name of a series (e.g., Delta Gap2 for Truck-Peacock refers to Peacock). All bold series names fit the CP restrictions. A series being labelled as CP needs to have both series names being bold. If not, series were labelled as no distinct pattern. The series are presented in alphabetic order. The last two columns represent the variance measures (Deviance_1 and Deviance_2) of the fit of the estimated curve of the observed data.

were interpreted as showing no distinct pattern. None of the series evolved in a pattern of morphing.

The distinction between CP series and non-CP series should also be reflected in the pattern of alternative responses; it was expected that a stronger increase of alternative responses would be observed for the non-CP series than the CP series. A sum of the number of alternative responses for each series on each morphing level reflected by percentages showed that a stronger increase of alternative responses was indeed obtained with increase of morphing level for the non-CP series compared to the CP series. This was statistically supported by the significant main effect of *CP* (CP series and non-CP series), $F(1, 13) = 17.44$, $p = .001$, and by the significant interaction effect between *CP* (CP series and non-CP series) and morphing (from 100%0% to 0%100%) on the percentage alternative responses, $F(8, 104) = 2.83$, $p < .01$. The stronger increase of alternative responses for the non-CP series compared to the CP series is graphically presented in Figure 6.

The described pattern of alternative responses suggests that the 50%50% figures for the non-CP series are difficult to recognize and therefore result in

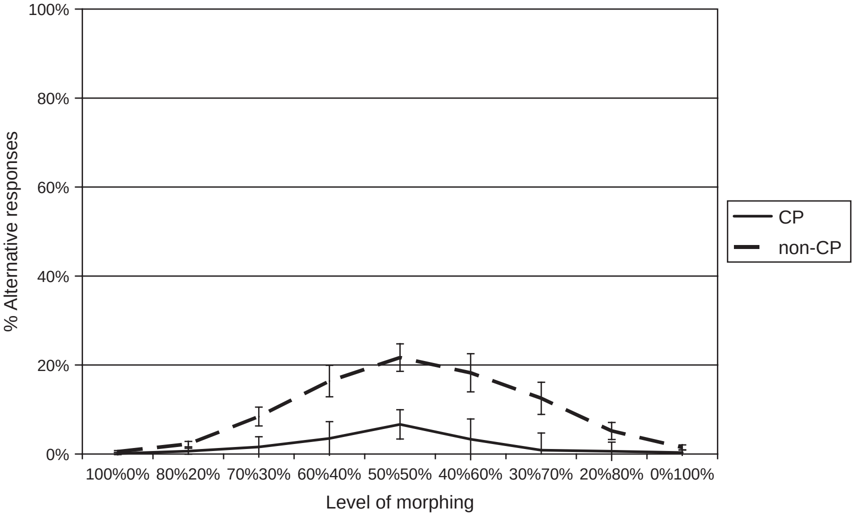

Figure 6. The percentage of alternative responses reported for the CP series and non-CP series in Experiment 1, with the different levels of morphing on the x-axis and the percentage of alternative responses on the y-axis.

a great number of alternative responses. One might think that this great number of alternative responses, in particular for the indefinable 50%50% figures of non-CP series, would affect the steepness of the slope for a non-CP series to such an extent that a pattern of CP is by forehand already impossible. We evaluated whether a free-naming pattern with a score of 0 for the 40%60% and 50%50% figure (indicating a score of 100 for the alternative responses) and a score of 100 for the 60%40% figure would lead to no distinct pattern. However, this pattern still resulted in a CP pattern, with naturally a X50 shifted towards the right ($X50 = 0.56$) and a Delta Gap still fitting the CP criteria ($G = 0.04$).

Discussion

Morphed figures were individually presented and were labelled using free naming. Patterns of CP of concrete objects were previously reported by Newell and Bülthoff (2002), but were found under conditions of forced choice. Interestingly, the current findings showed that CP also occurs for concrete objects when using a free-naming method. In total, seven out of fifteen series were categorically perceived. Notably, the remaining eight series showed no fit with either the patterns of CP or patterns of morphing. The findings of Experiment 1 provide more support that CP can be found for morphed figures of concrete objects as well. Subsequently, we examined whether the method used has different influences on CP by conducting a forced-choice experiment in Experiment 2.

EXPERIMENT 2

Method

Participants. Forty-four students from Utrecht University participated in this experiment. None of them participated in Experiment 1. The experiment lasted about 10 minutes and participants received a fee or course credits for their contribution.

Materials. All 135 figures used as stimulus materials in Experiment 1 (i.e., morphed figures and extremes) functioned as stimulus materials in this experiment. The black silhouettes were presented on a white background. The response possibilities were printed in black in font type Courier New and font size 24. The stimuli were displayed on a 17-inch monitor using E-Prime (Psychology Software Tools Inc., version 1.1) in a nonlit room. The viewing distance to the monitor was approximately 60 cm. Participants used a stimulus–response box (SR box) to enter their responses.

Procedure. Participants were asked to identify each morphed figure by choosing between two response possibilities. These possibilities were always similar to the dominant and nondominant interpretation of that particular object. For example, a figure from the series *Duck-Church* was always accompanied by the two response possibilities *duck* and *church*. Each trial started with a fixation cross (+) presented at the middle of the screen for 1000 ms. Next, the plus sign was replaced by a target (one of the figures from the stimulus material set) for a maximum of 10 s. Simultaneously to the presentation of the target, two words appeared on the screen below the figure at the left and right of the screen. These were the two response possibilities. Participants responded by pressing either the left button on the SR box if they thought the word on the left side of the screen corresponded most to the target or the right button of the SR box if they thought the right word corresponded most to the target. The moment a button was pressed, the target and response words disappeared and the next trial was initiated. Because our main interest was the identification of the objects, no time restrictions were included, except for the maximum of 10 s. By putting time pressure on responding, the chance of errors would increase, which would mean a loss of data. Furthermore, participants were instructed that this experiment was about their interpretation of the figures, and thus no correct or incorrect responses could be given. All figures were presented randomly, with the restriction that no two figures of the same series were presented sequentially.

Data analysis. The data were presented in a data matrix with all figures at the horizontal axis and all participants at the vertical axis. Each response was scored as either 0 or 1 referring to both interpretations of a series. For example, responses to a figure of the *Duck-Church* series were coded as 0 if they corresponded to *duck* and 1 to *church*. Because of the forced-choice method, no alternative responses were registered. This data matrix was used to measure the frequency percentages of a particular response. The graphs resulting from these frequency percentages presented the response patterns for each series separately.

Results

Of all data, 0.07% (4 out of 5940 trials) was excluded due to responses slower than 10 s. Subsequently, the data were analysed in the same way as in Experiment 1, except for the fact that instead of three types of answers (i.e., dominant, nondominant, and alternative responses), two answer types were analysed (i.e., dominant and nondominant responses). Using the Birmbaum Model, a curve with the best fit was calculated from which the Delta Gap and X50 could be inferred for each series separately. These values were compared to the values of the four data patterns of CP and of morphing. It was found that nine series out of fifteen showed a pattern of CP; the remaining six series showed no distinct pattern (see Table 2).

The CP series found in the forced-choice naming task were in order of strongest categorical to weakest categorical *Guitar-Sea Lion*, *Squirrel-Pram*, *Gun-Rabbit*, *Man-Lamp*, *Duck-Church*, *Cat-Butterfly*, *Bear-Bow*, *Turtle-Car*, and *Truck-Peacock*. The series showing no distinct pattern presented in an order of least noncategorical to most noncategorical were *Crocodile-Airplane*, *Arm-Banana*, *Heart-Apple*, *Hat-Bird*, *Bell-Kettle*, and *Dog-Gorilla*. None of the series showed a pattern of morphing.

Discussion

In this experiment, morphed figures were tested for patterns of categorical perception using a forced-choice method in which participants were forced to identify a morphed figure as its dominant or nondominant interpretation. The response patterns were analysed using the Birmbaum model. It was found that nine out of fifteen morph series showed a pattern of CP. The remaining six showed no distinct pattern, and no morph series showed a pattern of morphing. The lack of CP for these six series was caused for two

TABLE 2
The Delta Gap and X50 for all morph series tested in Experiment 2

Series	*Delta Gap*	*X50*	*Deviance*
Arm-Banana	0,28	0,43	11,3
Bear-Bow	0,20	0,53	10,1
Bell-Kettle	0,25	0,39	29,8
Cat-Butterfly	0,03	0,59	12,3
Crocodile-Airplane	0,27	0,57	11,8
Dog-Gorilla	0,24	0,62	7,5
Duck-Church	0,07	0,57	9,2
Guitar-Sea Lion	0,12	0,47	13,4
Gun-Rabbit	0,13	0,46	2,0
Hat-Bird	0,34	0,44	33,1
Heart-Apple	0,26	0,58	17,9
Man-Lamp	0,19	0,48	12,6
Squirrel-Pram	0,18	0,49	12,8
Truck-Peacock	0,16	0,44	0,0
Turtle-Car	0,12	0,44	10,3

When the name of a series is bold, this indicates that the Delta Gap and X50 of that series fit the CP-restrictions. The series are presented in alphabetic order. The last column presents the variance measure (Deviance) of the fitted function on the observed data.

series by an early switch in percept instead of a switch halfway the continuum. The remaining four non-CP series showed a pattern that was not linear enough to fit the criteria of a pattern of morphing and not discrete enough to fit a pattern of CP. Despite the fact that not all series showed CP, these data suggest that a majority of the morph series used in this study was perceived categorically.

EXPERIMENT 3

In Experiments 1 and 2, the observation of CP for familiar objects was confirmed. Not all morph series showed a pattern of CP, however. Furthermore, not all series showed the same pattern for both methods. From these findings the question is raised why some series are perceived categorically and others not.

Notably, the different effects the morph series had on CP could not be explained by image differences on pixel level (i.e., we calculated the luminance differences between all figures of a morph series and compared these pixel differences between the CP series and non-CP series). In other words, some series showed a larger increase in difference in number of pixels between extreme and morphed figure than other series, but this difference in changes was not consistently larger for either CP series or non-CP series.

Moreover, Newell and Bülthoff (2002) argued that whether a series shows CP or not depends on the strength of perceptual similarity between the extremes. They reported a positive correlation between CP and similarity in shape. Therefore in the current experiment, we examined whether our dataset supported this claim. Similarity was assessed for a number of features; we distinguished perceptual similarity into subdivisions of shape (i.e., referring mainly to general contours), number of parts and intrinsic part structure (Rosielle & Cooper, 2001). Moreover, a number of studies (Biederman, 1987; Biederman & Gerhardstein, 1995) have suggested that categorization is often component based; therefore, number of parts and intrinsic part structure could be valuable additions to investigate perceptual similarity. Things that look the same are also often connected in other respects, such as in meaning and general semantics (Rosch et al., 1976). We therefore also compared the semantic similarity ratings, and finally the phonological similarity ratings, between the categorical and the noncategorical series. Because the division of CP series and non-CP series was different for the free-naming and forced-choice experiments, we ran two analyses to find out whether perceptual similarity plays an important role for one or both methods.

Method

Participants. Twenty students from Utrecht University participated in Experiment 3. The experiment lasted about 20 minutes, and the students were paid a fee or course credit for their participation. All participants had normal or corrected-to-normal vision. All participants had Dutch as their native language. None of them had participated in Experiments 1 and 2.

Materials. The stimuli that were used were the extremes (100%0% and 0%100%) of each morph series tested in Experiments 1 and 2. The stimuli were presented on a computer using E-Prime (Psychology Software Tools Inc., version 1.1) in a nonlit room. Participants used a standard keyboard to enter their responses.

Procedure. The experiment contained five blocks in which the two extremes were compared on five different aspects: Shape, semantics, phonology, number of parts, and intrinsic part structure. The five aspects were always presented in the order as reported here, which was based on an increase in difficulty. Within each block, trials were presented in a new random order for each participant.

The presentation of the experimental trials was the following: At the top of the screen the question "How strong is the similarity between the two figures in . . .?" was presented in Dutch. The dots were replaced by the aspect investigated in that particular block. In the middle of the screen the two extremes of a morph series were presented next to one another. A rating scale from one to seven was presented at the bottom of the screen with at the left end the word *weak* and at the right end the word *strong*. Participants were instructed to enter a number from one to seven. They were encouraged to use the entire range of the rating scale. Participants viewed what they were typing below the rating scale. When participants agreed on their response, they pressed the enter button to continue to the next trial. Alternatively, they could use the backspace button to correct it. Participants were given ample time to respond to each trial.

Each block was preceded by instructions about the particular aspect examined. For instance, participants were presented with three examples to illustrate what the idea was behind comparing shape. The first example was always a written example; for instance, a *warning triangle* and a *wedge of cake* imply high similarity in shape, but a *warning triangle* and a *traffic light* do not. Next, participants were presented with a good example followed by a bad example. For these illustrations, silhouette figures were used which were also based on the line drawings of Snodgrass and Vanderwart (1980), but none was similar to the silhouette figures used in the experimental trials. For example in the shape block, *bottle* and *candle* were used as a good example and *camel* and *boat* were used as a bad example.

Data analysis. Two groups were created: Categorical series (CP series), consisting of the categorically perceived series, and noncategorical series (non-CP series), consisting of the noncategorically perceived series. The division of the 15 morph series in these two groups varied for Experiments 1 and 2. These two groups were compared for their similarity ratings on five different aspects: Shape, semantics, phonology, number of parts, and intrinsic part structure.

Results

First, an overall correlation test was performed to investigate possible correlation patterns between the different aspects. A priori, one might expect that the three aspects concerning perceptual similarity (shape, number of parts, and intrinsic part structure) were correlated. It was found that number of parts and intrinsic part structure were the only two aspects that were significantly correlated, $r = .670$, $p = .001$. This meant that the similarity ratings on most aspects were not influenced by similarity ratings on other aspects, except for number of parts and intrinsic part structure. An object containing a certain number of parts might have a fixed way in which it is structured. For example, an object with five parts could contain one component in the middle and four components around this centre part, which might underlie the observed correlation between number of parts and intrinsic part structure.

Subsequently, the two groups of CP series and non-CP series were compared for each aspect separately running Analyses of Variance using repeated measures in a 2 × 5 within-subject design. The variables categorical perception (CP series and non-CP series) and aspect (shape, number of parts, intrinsic part structure, semantics, and phonology) were used as within-subject variables. Significant effects found at an alpha level of .05 were investigated further by conducting Bonferroni post hoc comparisons.

The main effect of aspect was significant, $F(4, 76) = 67.21$, $p < .001$. Post hoc comparisons showed that almost all aspects differed significantly, $F(4, 16) = 29.68$, $p < .001$, except for the aspects of number of parts and intrinsic part structure and for the aspects of semantics and phonology. The highest similarity ratings were assigned to the aspect of number of parts followed by intrinsic part structure, shape, semantics, and phonology. The effect of aspect was similar for the CP and non-CP series of the forced-choice and the free-naming experiments, because this effect was independent of CP.

The main effect of categorical perception and the interaction effect between categorical perception and aspect are, due to a difference in the division of CP series and non-CP series, reported separately for the free-naming experiment and the forced-choice experiment.

Free-naming division CP series and non-CP series. We compared the CP series to the non-CP series based on the findings of the free-naming experiment. The main effect of categorical perception was significant, $F(1, 19) = 36.49$, $p < .001$, with higher similarity ratings for the CP series than for the non-CP series. Furthermore, the interaction effect of categorical perception and aspect was also significant, $F(4, 76) = 28.94$, $p < .001$. Bonferroni comparisons revealed that the aspects on perceptual similarity all showed higher ratings for the CP series in comparison to the non-CP series, $F_{shape}(1, 19) = 8.06$, $p = .010$, $F_{parts}(1, 19) = 33.91$, $p < .001$, $F_{structure}(1, 19) = 55.98$, $p < .001$, whereas the non-CP series showed higher similarity ratings on the aspect of phonology than the CP series, $F_{phonology}(1, 19) = 9.79$, $p < .01$, and did not differ from one another on the aspect of semantics, $F_{semantics}(1, 19) = 0.30$, $p > .05$. In Figure 7, the means and standard errors for the free-naming as well as the forced-choice distinction of the CP series and non-CP series on the five different aspects of similarity are presented graphically.

The finding that the extremes of CP series were rated more perceptually similar than the extremes of non-CP series suggests that CP and perceptual similarity might be positively correlated. Therefore, we ran a regression in which the morph series were ordered from least categorical to most categorical in an ordinal way using *z*-scores based on the two Delta Gap

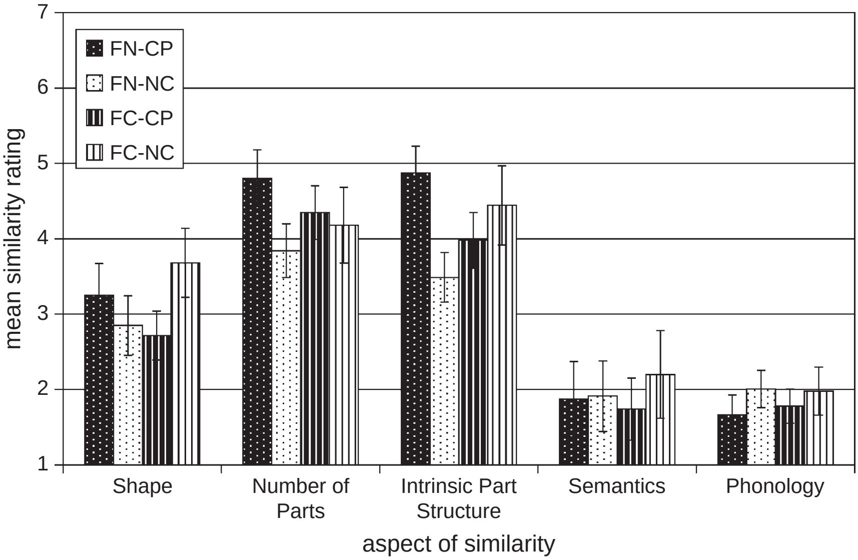

Figure 7. The means and standard errors for all five aspects of similarity, with the dark dotted bar and the light dotted bar representing the CP series and non-CP series of the free-naming experiment, and the dark striped bar and the light striped bar representing the CP series and non-CP series of the forced-choice experiment. On the x-axis the five aspects of similarity are outlined. The y-axis represents the rating scale from 1 to 7 with an increase in similarity rating.

and two X50 values of each morph series. The regression including the three aspects of perceptual similarity was not significant, $F(3, 11) = 1.74$, $p = .217$, $R^2 = .321$. This means that no significant relation was found between strength of CP and amount of similarity on any of the aspects, $r_{shape} = .058$, $p = .836$; $r_{parts} = -.387$, $p = .154$; $r_{structure} = -.459$, $p = .085$; $r_{semantics} = .197$, $p = .482$; $r_{phonology} = .256$, $p = .357$. Importantly, the analysis of variance apparently showed clear differences for CP series versus non-CP series.

Forced-choice division CP series and non-CP series. We found opposite patterns for the results of the ANOVA with categorical perception and aspect as within-subject variables based on the forced-choice division of CP series and non-CP series in comparison to the analysis of the free-naming division. The main effect of categorical perception was significant, $F(1, 19) = 61.69$, $p < .001$. Unexpectedly, the extremes of the non-CP series were rated more similar than the extremes of the CP series. The interaction between categorical perception and aspect was also significant, $F(4, 76) = 8.83$, $p < .001$. Conducting pairwise comparisons (Bonferroni corrected), the aspects of shape, $F(1, 19) = 123.02$, $p < .001$, intrinsic part structure,

$F(1, 19) = 5.48$, $p < .05$, and semantics, $F(1, 19) = 54.32$, $p < .001$, differed significantly for the CP series and the non-CP series, with higher similarity ratings assigned to the extremes of the non-CP series than the CP series. The aspects of number of parts and phonology were not significantly different between the CP series and non-CP series.

Discussion

In Experiment 3, the two extremes of all 15 morph series used in Experiments 1 and 2 were tested for their similarity on different aspects: Shape, number of parts, intrinsic part structure, semantics, and phonology. The similarity ratings for each aspect were compared between the CP series and non-CP series for the two different divisions found under conditions of free naming and forced choice. The two methods showed diverging data patterns of similarity ratings between CP series and non-CP series. For the free-naming distinction, the three aspects of perceptual similarity all showed higher similarity ratings for the CP series in comparison to the non-CP series, but a linear relation between order of CP and degree of perceptual similarity was not found, possibly due to the order of series from most categorical to least categorical which was somewhat arbitrarily chosen. In contrast, for the forced-choice division, the perceptual similarity aspects of shape and intrinsic part structure showed higher similarity ratings for the non-CP series than for the CP series. In addition, the aspect of number of parts was not different for the two types of series. Noteworthily, the group of CP series consists of more series than the group of non-CP series as a result of the forced-choice experiment (nine CP series to six non-CP series), while the distribution of the CP series and non-CP series as a result of the free-naming experiment is more or less equal (seven CP series to eight non-CP series). The skewed distribution of CP and non-CP series by the forced-choice method might have biased the findings of the analyses on the relation between perceptual similarity and CP.

Furthermore, phonological similarity was quite low in absolute sense (i.e., a score between 1 and 2 on a rating scale of 1 to 7), indicating that the sound pattern of object names does not affect the way they are visually perceived. This implication was reinforced by the fact that the low similarity effect on the aspect of phonology could not be due to variability in the names used for rating the objects on their phonological similarity: 91% of the participants used the same names for the objects. Moreover, semantic similarity ratings were also low for both types of groups suggesting that the general meaning of an object category does not contribute to the categorical perception of a morphed figure.

GENERAL DISCUSSION

The goal of this study was to explore whether higher level visual constructs such as morphed objects are perceived and interpreted in a continuous fashion or more categorically. We obtained support for CP of concrete objects in Experiments 1 and 2 by showing that CP not only occurs under circumstances of forced choice, but also under circumstances of free naming. These results extend the findings by Newell and Bülthoff (2002), who also found CP for familiar objects.

Notably, the free-naming and forced-choice experiments showed differences in which particular series were identified as yielding CP.[1] Four series that showed strong CP in the free-naming experiment also had a strong CP pattern in the forced-choice experiment. However, five series that were perceived categorically using forced choice were not perceived categorically in the free-naming experiment. The latter finding illustrates that forced-choice methodology evokes more CP. Most importantly, three series that were labelled as non-CP series in the forced-choice experiment were perceived categorically under conditions of free naming. We may consider two reasons for this latter difference. One concerns the fact that in the free-naming experiment participants were not restricted to two options only, but also could give an alternative response. The other reason for the limited overlap in CP series between the two experiments could be that, in a forced-choice task, one is presented with both response options, whereas in a free-naming experiment one has to retrieve the answer oneself. Both reasons make clear that free naming resembles a more natural method (Malt & Sloman, 2007) to identify objects under circumstances of perceptual uncertainty.

As was implied by Newell and Bülthoff (2002), CP might be a mechanism to discriminate especially between perceptually similar objects, in particular objects from the same (basic-level) category. In Experiment 3, we confirmed this hypothesis for the free-naming distinction of CP series and non-CP series: Extremes of series labelled as categorically perceived were rated as more perceptually similar than extremes of series labelled as noncategorically perceived, even though the stimulus materials consisted only of between-category objects. In contrast, the effect observed for the forced-choice distinction of CP and non-CP series showed a higher similarity rating for the non-CP series than the CP series. Notably, this result might be biased by the skewed distribution of number of CP series and non-CP series

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[1] We acknowledge that labelling a series as CP or non-CP is slightly arbitrary and is an example of dichotomous categorization itself. However, we argue that our distinction is defendable; CP is a well-described phenomenon in the literature from which we have inferred conservative criteria that a series should fulfil before being labelled as a CP series.

(i.e., nine vs. six, respectively). The current results therefore show that perceptual similarity indeed plays an important role in categorizing morphed figures, but only in more natural circumstances, such as free naming. Interestingly, Newell and Bülthoff found a positive correlation between perceptual similarity and amount of categorical perception, despite the fact that they used a forced-choice method. It has to be noted that the forced-choice method they used did not rely on stored concepts; participants were asked to choose between two images, instead of words like the current experiment. Therefore, participants in the study of Newell and Bülthoff could have visually compared the images to the morphed figure. This discrepancy might explain the differences between the two studies.

The foregoing findings appear to form a rather elegant illustration of a recent Bayesian model of Feldman and Singh (2006), in particular for the relation between CP and perceptual similarity. This model is used to compute the so-called optimal skeletal representation of an object (i.e., MAP skeleton). A shape skeleton represents an object in the simplest, generative manner by translating an object into branches and subbranches, each representing a component of that object. By this method a unique skeletal representation can be derived for each object. If two extremes are judged as perceptually similar, they probably have closely related skeletons. By morphing perceptually similar extremes, their skeletal representations will change with small steps. Because of the robustness to small changes, a skeletal representation will keep its unique appearance until the category boundary is reached (at which the skeleton will adopt characteristics of the other extreme's skeleton). In Experiment 3 and in particular for the division of CP- and non-CP series by the free-naming experiment, we found that perceptual similarity ratings were highest for CP series on the aspect of intrinsic part structure. This assumption provides support for objects being categorized by their skeletal representation, because the intrinsic part structure seems to have much in common with the model of shape skeleton. This model also explains why perceptually dissimilar extremes would not show a pattern of CP. The skeletal representation of these extremes varies to a great extent, enhancing the opportunity to form a new, distinctly different skeleton within a morphing series. This new skeletal representation might resemble a third category or a new unknown (i.e., yet undefined) category. Moreover, studies on changes to an object, such as rotation (Wallis & Bülthoff, 2001) and different viewpoints (Newell & Bülthoff, 2002; Newell & Findlay, 1997), reported that these changes did not affect categorization of the objects. Again we may speculate that this is because the skeleton frame is preserved throughout these changes.

Based on the association between perceptual similarity and CP, we argue that it is the intrinsic part structure of a morphed figure that is probably used to categorize an object. If two perceptually similar objects are morphed, this intrinsic part structure is less distorted than when two perceptually dissimilar objects are morphed. These small distortions caused by perceptually similar objects might result in still recognizing the morphed figure as a member of the same category as its dominant extreme.

The latter speculations also fit the general assumption that categorization is based on similarity (Edelman, 1995, 1998; Hahn & Ramscar, 2001; Hampton, Estes, & Simmons, 2005; Rosch et al., 1976). Morphed figures at the first half of a continuum share enough features to be categorized as the same object. However, halfway along the continuum these features have changed so much that they no longer will fit the characteristics of that particular category. Thus, figures on one half of the continuum could have been identified on basis of their similarities, whereas figures halfway along the continuum could be identified differently on basis of their lack in similarities.

Notably, what makes morphed figures unique is the combination of two extremes. Although the dominant one is perceived in many of the series, it would be interesting to investigate to what extent the nondominant interpretation has any effect on the visual processing of morphed figures. This could be examined by investigating influences of top-down information by conducting a priming experiment in which a prime congruent to the nondominant interpretation preceding a morphed figure could affect interpretation of the morphed figure or not. Moreover, a priming experiment may crystallize the underlying mechanism of CP further.

CONCLUSION

Support of categorical perception of objects was provided by showing patterns of CP under conditions of forced choice and free naming. In the free-naming experiment half of the series fitted the pattern of CP. This may be due to perceptual similarity between the extremes of a morph series; high ratings on perceptual similarity were strongly associated with categorically perceived series. Moreover, the series that showed a CP pattern in the free-naming experiment did not necessarily show a CP pattern in the forced-choice experiment. The distinction between CP series and non-CP series resulting from the forced-choice experiment could not be explained by perceptual similarity. We would like to argue that free naming is a more natural way of investigating CP (see also Malt & Sloman, 2007).

Since we found CP in the current study for concrete objects, we would like to argue that the phenomenon of CP is not limited to biological predispositions. CP shares many characteristics to the general process of categorization by assigning figures to the same category when they share many features, but assigning them to different categories when they share few or none features. It might be the strength of violations to the intrinsic part structure caused by the morphing procedure that makes a morph series being perceived categorically or not. A similar process might be underlying categorization in general. Therefore, CP probably is a submechanism of categorization which specifically deals with perceptual uncertainty by focusing on visual features of an object to fit it into a category.

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Manuscript received February 2009
Manuscript accepted March 2010
First published online July 2010