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**Interactions between view  
changes and shape changes in  
picture-picture matching**

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# Interactions between view changes and shape changes in picture-picture matching

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**Abstract.** Four studies presented pictures of different morphs of novel, complex, three-dimensional objects, similar to objects which we must identify in the real world. We investigated how viewpoint changes influence our ability to discriminate between morphs. View changes had a powerful effect on performance in picture-picture matching tasks when similarly shaped morphs had to be discriminated. Shape changes were detected faster and more accurately when morphs were depicted from the same rather than different views. In contrast, view change had no effect when dissimilarly shaped morphs had to be discriminated. This interaction between the effects of view change and shape change was found for both simultaneous stimulus presentation and for sequential presentation with interstimulus intervals of up to 3600ms. The interaction was found following repeated presentations of the stimuli prior to the matching task and following practice at the matching task as well as after no such pre-exposure to the stimuli or to the task. The results demonstrate the importance of view changes relative to other task manipulations in modulating the shape discrimination abilities of the human visual recognition system.

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In this paper we examine interactions between the effects of view changes and shape changes on object recognition. The human visual object recognition system must achieve object constancy over view changes in order to reliably identify objects as members of a class of familiar stimuli such as dogs or chairs or apples. To do this, it must often ignore considerable variation in the visual input due to semantically irrelevant changes in the viewing conditions such as alterations in the lighting conditions and in the position of the observer relative to the object. Achieving object constancy allows us to generalise over variation in illumination, viewpoint, size and retinal position, all of which produce changes to the visual input which should be ignored because they do not alter the identity of an object.

In contrast to these semantically irrelevant view changes, a shape change often does affect important semantic category information about an object. Quite small shape changes can alter a drawing pin to a nail, a mug to a jug, a stool to a table, and so on. Not all shape changes are important - many minor shape changes are semantically irrelevant and so should be ignored, such as the variability in the shape of wine glasses, trees and knives. There are also some major shape changes which should be generalised over. For example, animals change their shape radically as they move to different positions, yet we need to identify a running dog and a sitting dog as belonging to the same semantic category. Overall, though, unlike view changes, shape changes are often semantically meaningful.

There will often be conflict in the attempt to optimise the achievement of these two goals of the visual system, namely achieving object constancy by generalising over semantically irrelevant view changes whilst being sensitive to shape changes in order to discriminate between semantically distinct categories of objects. If the differences in the visual input due to view changes were distinct in nature from the differences caused by shape changes, or much smaller, then this trade-off could be avoided. Unfortunately, though, view changes and shape changes often result in similar effects on the visual input stimulus. Rotations in depth can alter the global outline shape of an object and the visibility, size and apparent spatial relations between parts of the object, all of which can also result from shape changes. Any attempt to improve the process of achieving object constancy will therefore risk reducing the accuracy of object discrimination and vice versa. The visual system must therefore try to reach an appropriate compromise in achieving these two aims. In the current paper, we examine empirical evidence for a trade-off.

As noted by Cutzu and Edelman (1998), most studies of object recognition and categorisation to date have either manipulated view changes whilst maintaining shape constant or have manipulated shape changes whilst maintaining view constant. In addition, whilst the former area of research in object recognition has tested a range of stimuli from complex, naturalistic, three-dimensional objects to more simple stimuli, in the latter area of object categorisation research, most

studies have tested only simple, impoverished stimuli such as colour patches or geometric shapes. As a result there are almost no data on the effects of view changes on the ability to discriminate shape changes for relatively complex, realistic stimuli. Exceptions to this are the studies reported by Cutzu and Edelman (1998) and by Hayward and Williams (2000) which are described below.

View sensitivity can be defined as a difficulty or even a failure to achieve object constancy when there are view changes across stimuli which must be identified as being from the same category. View sensitivity is therefore a measure of the difficulty of achieving object constancy, and so of the effect of view changes on our ability to recognise objects. It has often been assumed that view sensitivity increases as the difficulty of shape discrimination increases (for example, if an animal has to be identified as a dog versus a cat rather than as a dog versus a table; or if a face has to be named rather than just discriminated from a non-face). Evidence in support of this hypothesis comes from studies of picture-word verification of brief, masked, plane-rotated views of familiar objects, where view sensitivity increased as the visual similarity between the shapes of competing response alternatives increased (Lawson & Jolicoeur, 1998, submitted). Here, upright and, to a greater extent, disoriented stimuli were harder to identify when stimuli were more difficult to discriminate. Thus the effect of view changes interacted with the ease of shape discrimination.

Hayward and Williams (2000) failed to find an interaction between the effects of view changes and the difficulty of discriminating shape changes. They manipulated the ease of shape discrimination across blocks in a speeded sequential picture matching task which presented different views of novel, complex objects. When mismatch trials on a block presented only visually dissimilar items, there were increases in both RTs and error rates on match trials as the depth rotation between the two pictures increased. Importantly, this view sensitivity for match trials was not reduced relative to blocks when mismatch trials presented only similar items. Hayward and Williams (2000) concluded that view-sensitivity is generally not affected by varying the context of shape discriminability by manipulating shape similarity on mismatch trials (except when view-invariant distinguishing information is readily available, as was the case in their first study, where stimuli could be discriminated by colour in the visually dissimilar context condition). Instead they suggested that the intrinsic geometry of objects determined view effects independent of the task context.

Hayward and Williams (2000) examined the effects on match performance of manipulating the similarity

of mismatch shapes across different blocks. In contrast, the current studies examined the effects on match and mismatch performance of manipulating the size of shape changes within a block. Although the tasks and stimuli tested across these studies superficially appear similar, the two sets of studies address different issues. Hayward and Williams' (2000) studies suggest that view sensitivity on match trials is not influenced by the overall difficulty within a block of detecting whether two shapes are identical. The current studies investigate how view sensitivity is influenced by the shape similarity on mismatch as well as on match trials, given a constant overall level of difficulty of shape discrimination within the context of the task.

Visual similarity is likely to play a crucial role in understanding how view sensitivity affects object recognition. It is, though, difficult to both produce a meaningful and accurate measure of the perceived visual similarity in shape of two objects and to systematically vary the difficulty of shape discrimination by manipulating visual similarity. This is particularly true for familiar, complex, three dimensional objects such as dogs, chairs and apples, which have to be identified in everyday object recognition. The visual similarity in shape between two such objects can be measured using physical measures, subjective ratings and confusion errors, but there are significant problems with all such measures (Lawson & Jolicoeur, submitted). Furthermore, visual similarity cannot be manipulated systematically, since familiar objects with a pre-specified level of visual similarity to other familiar objects cannot necessarily be found or created. Some familiar objects do have a number of highly visually similar neighbours (horse has donkey; car has van) but many objects do not, and even if visually similar neighbours are available, their similarity is difficult to measure meaningfully and accurately.

Recently, pairs of visually similar, familiar objects have been used as two endpoint objects and a series of intermediate, morphed objects have been produced, with each morph varying in shape in a systematic way from the others in the series. To date, this has been done most often with faces (e.g., Beale & Keil, 1995; Campanella, Chrysochoos & Bruyer, 2001), but it is possible with other objects. Such stimuli are generally labour-intensive to produce as the morphing process typically requires that many equivalent points across the two endpoint objects be identified by the experimenter (such as the tips of the ears and the middle of the back of the horse and the donkey) in order to map between the two shapes.

Novel stimuli made of bent wires or a small number of generic volumetric parts have been used by researchers investigating object recognition. An advan-

tage of such novel objects is that a range of visually similar versions can be produced relatively easily. Furthermore, straightforward subjective ratings or physical measures of shape similarity provide a reasonably meaningful estimate of the perceived visual similarity of such shapes, enabling experimenters to quantitatively manipulate shape changes across a series of stimuli. Note, though, that an important difficulty with many such novel stimuli, particularly those like the bent paperclips which the visual system seems to have particular difficulty representing, is that they may differ in significant ways from the familiar objects that our visual system has evolved to recognise. Conclusions drawn from performance with such novel stimuli may not generalise to more ecologically valid stimuli.

Cutzu and Edelman (1998) used stimuli which addressed many of the difficulties outlined above in trying to vary visual similarity for either familiar or novel objects. They tested a range of morphs, all of which were derived from a single, complex animal-like novel object. Each morph was defined by values of 70 parameters which specified the shape of the object parts and their spatial relations relative to the other object parts. Sets of morphs were presented to participants, with the relative shapes of the morphs selected to be arranged in a known configuration (such as a triangle) in the abstract shape space defined by these 70 stimulus-defining parameters. Participants rated the perceived similarity of different pairs of morphs which were presented simultaneously, with each morph being shown rotating continuously in depth. Non-metric multidimensional scaling techniques were then used to transform these ratings of morph similarity into psychological (not physical) distances in a low-dimensional similarity space. The configuration of positions of the morphs in this psychological space was consistently found to reflect their positions in the original parameter space (such as a triangle in both cases). This suggests that manipulations of the physical parameters systematically influenced the perceived similarity of the morphs and that participants used this information to extract the parameterised similarities which had been imposed on the morphs.

Cutzu and Edelman (1998) also ran speeded sequential matching studies with pictures of two different views of either the same or of different morphs. Participants received no prior training with the stimuli and no feedback during the task. Nevertheless, as for the unspeeded rating task described above, the results of the matching task allowed a recovery of the configuration of the morph stimulus positions which had been set in the parameterised physical shape space from the positions of the stimuli in the psychological similarity space. Importantly, the position of different

views of the same morph in the psychological space were generally clustered together, indicating that participants were matching on shape similarity whilst ignoring variation in viewpoint to achieve object constancy.

Finally, the parameterised shape space was once again recovered from human psychophysical data using the results of a long term memory rating task. Here, participants first learnt to associate novel words to different test morphs. They then had to rate the similarity of pairs of the test morphs to each other given only the verbal labels of the morphs (“is A more similar to B than C is to D?”). In this task, the test morphs were never seen together. During training, only one test morph was seen during a given training session, presented from a range of views rotated in depth. Participants learnt to discriminate that test morph from a set of different views of non-test distractor morphs which were similar to the test morph. Participants were not told that they would subsequently have to compare the test morphs. During testing, no morph pictures were presented, forcing participants to rely on their long-term memory of the test morphs. This task therefore required access to stable memory representations whereas the rating and sequential matching tasks could have relied on only transient perceptual representations. Nevertheless, the three tasks produced similar results. Cutzu and Edelman (1998) argued that the consistency of results across the different tasks suggests that all three tapped common representations which were structured according to similarity.

Cutzu and Edelman (1998) also tested two models of similarity. The first was an image-based model. This was found to group the morphs by similarity in view rather than shape, indicating that for the animal-like morphs tested by Cutzu and Edelman, similarity in view was more salient in the image than similarity in shape. This model failed to replicate the human participants’ perceived similarity shape space derived from multidimensional scaling. The second model was a set of radial basis function networks, each of which was initially trained to associate together all views of a particular morph. When tested with novel stimuli, this model, like the human participants, produced a similarity measure which, when analysed using multidimensional scaling, resembled the parameterised morph space.

The results from Cutzu and Edelman’s studies suggest that humans can represent the similarity in shape between novel morphs of complex objects in a relatively view-invariant manner. This was in spite of view changes apparently having at least as important an effect on the image as shape changes, as evidenced by the results of their first, image-based model, which

grouped morphs by similarity in view. Cutzu and Edelman did not, though, experimentally test the relationship between view changes and shape changes. In both their short and long term rating studies, participants were exposed to many different views of the morphs, and only overall the similarity between pairs of morphs was rated (i.e., averaged over all views). In the sequential matching studies, all trials depicted two pictures of morphs from very different views in depth, so the effects of small versus large view changes were not compared. In the current studies, we focussed on examining the relation between view change and shape change, to examine whether the size of view changes influences our ability to detect shape changes.

Like Cutzu and Edelman (1998), we presented views of sets of morphs of novel objects. The objects were derived from familiar, everyday objects and were intended to resemble such objects more closely than most novel stimuli which have previously been used. Relative to other novel stimuli, the present set of objects were generally more complex and had more varied shapes. In addition, the objects were not generated from a simple alphabet of geometric parts. Instead, the objects varied in their number of parts and in the size, shape and spatial arrangement of parts. Finally, morphs derived from many different objects were used in the current studies, whereas Cutzu and Edelman (1998) used morphs derived from a single object in their studies.

We produced thirty sets of morphed stimuli, with each set being derived from a single, three dimensional model of a real object such as a cannon, a roller-skate or a dog. The selected model of a real object was then morphed to produce the endpoint morph, S1. S1 did not closely resemble the original object model, although in some cases it could be identified as being derived from the model. S1 was then morphed in a different way to create a series of twelve morphs from S2 to S13, such that the nature and degree of physical shape change produced by the morphing changed incrementally from each morph to the next in the series, see Figure 1a. The nature and extent of the shape change between S1 and S13 differed for each of the thirty objects. All of the object or separate parts could be squashed, expanded or twisted. This morphing technique avoided the technical and theoretical difficulties of attempting to find equivalent, corresponding points between two familiar endpoint objects which occur when, for instance, morphs are required between two faces. Finally, for each of the thirteen morphs, S1 to S13, twelve different views in depth were produced, with each view being rotated by 30° from the next.

Since the shape changes across each set of 13 morphs were well-controlled, these stimuli allowed us

to explore the effects of incremental shape changes for each of the thirty different novel objects. It is, nevertheless, important to emphasise that the size and nature of the perceived change in shape probably varied somewhat from one pair of morphs to the next in each morph series. It is, though, likely that the perceived visual similarity in shape between the S1 morph and the other morphs did at least monotonically decrease from S2 to S13, even if the magnitude of the reduction in similarity from one morph to the next varied somewhat. Cutzu and Edelman's (1998) rating studies measuring perceived similarity for different morphs also support this assumption.

The current studies investigated how view changes caused by depth rotation influence the sensitivity of participants to shape changes produced by morphing. This was investigated in four matching studies which tested both simultaneous and sequential picture presentation, and which depicted morphs from the same and from various different views. On match trials, pictures of the same morph (e.g., both S1) of the same novel object were presented. On mismatch trials, pictures of two different morphs (e.g. S1 and S10) of the same novel object were presented, see Figures 1b and 1c. Thus since on mismatch as well as match trials, morphs derived from the same novel object were depicted, then unlike most previous studies of the effects of view change on picture matching (e.g., Bartram, 1976; Ellis & Allport, 1986; Ellis, Allport, Humphreys & Collis, 1989; Hayward & Williams, 2000; Lawson & Humphreys, 1996), results from mismatch as well as match trials are readily interpretable and theoretically interesting. Measuring view change across pictures of two different objects is only meaningful when the depicted view of both objects can be described using the same reference frame. This was the case for the two morphs which were presented on mismatch trials here, which always shared the same general shape, see Figure 1. In contrast, in most picture matching studies to date, mismatch trials presented two objects that were selected at random from a diverse set of stimuli, so the mean shape similarity between the objects was low, and similarity varied greatly and in an uncontrolled way from trial to trial. For example, a mismatch trial might present a side view of a dog followed by a front view of a banana. A measure of view change on such a trial is almost meaningless, as there is little or no relation between the front views (or any other views) of the two objects as they have such different shapes.

## 1 Experiment 1

In Experiment 1, we investigated the relation between the effects of view changes and shape changes on the accuracy of simultaneous picture matching. Based

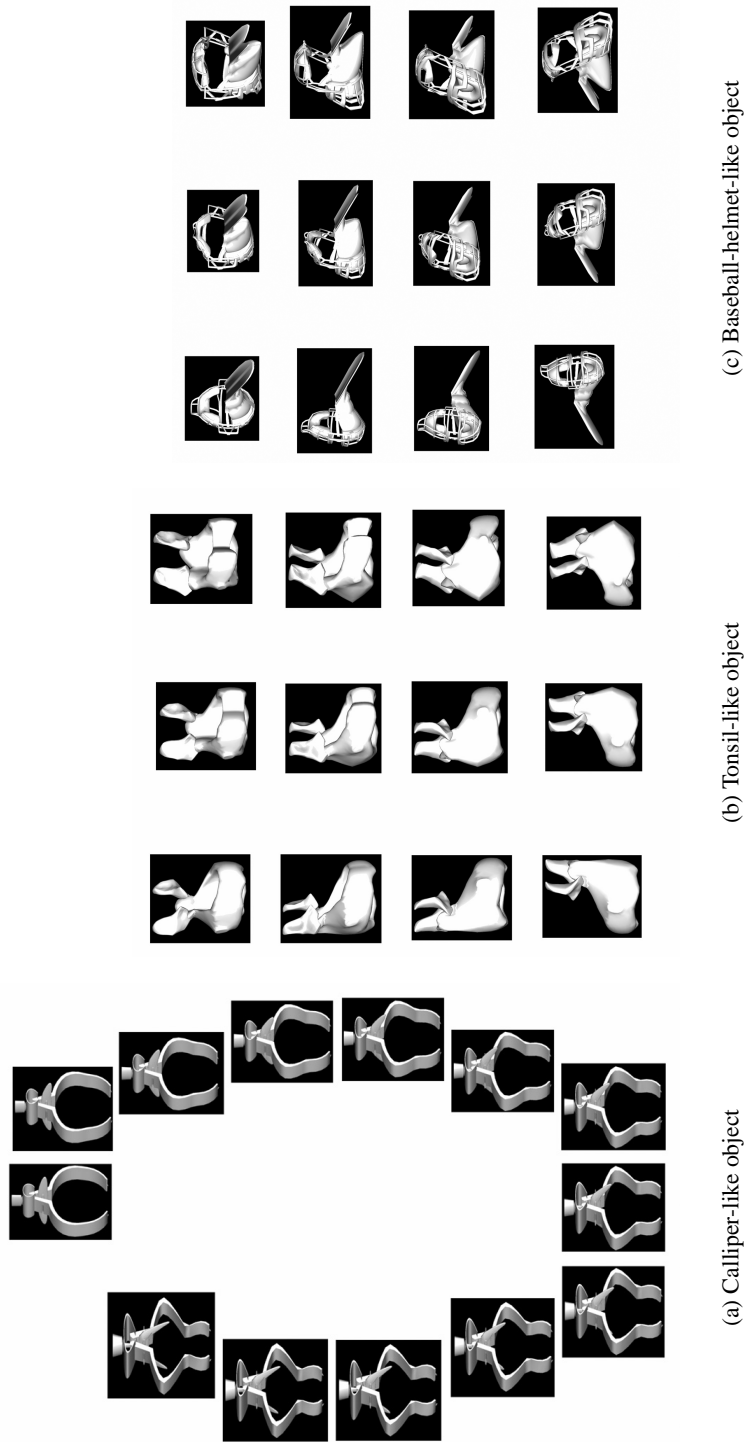


Figure 1: Pictures of three objects which were presented in all of the studies described in this paper. (a) the thirteen different morphs of a calliper-like novel object, all depicted from a  $30^\circ$  view, starting, top centre, with S1 and finishing, uppermost left, with S13; (b) the tonsil-like novel object and (c) the baseball-helmet-like novel object, which were depicted from  $30^\circ$ ,  $60^\circ$ ,  $120^\circ$  and  $240^\circ$  views (from top to bottom respectively) of the S1, S7 and S13 morphs (in the left, centre and right columns respectively).

on results indicating that making shape discrimination harder by increasing visual similarity in turn increases view change effects (Lawson & Jolicoeur, 1998, submitted), we predicted that view sensitivity would increase systematically as the shape change between two objects decreased. In Experiment 1, we wanted to examine the extent of any such view-sensitivity over a wide range of shape changes. Note that this prediction runs counter to the suggestion from the matching studies of Cutzu and Edelman (1998) that the representation of shape similarity is relatively view-invariant, and that view change and shape change effects do not interact. As discussed above, though, the effects of varying view change on shape discrimination was not explicitly tested in their studies.

In Experiment 1, participants were simultaneously shown two pictures, both depicting morphs derived from the same object. On "same" match trials, both pictures depicted the same S1 morph of the object. On "different" mismatch trials, one picture showed the S1 morph whilst the other picture showed the S2, S3, S5, S7 or the S13 morph. The most dissimilar stimuli were seen on S1-S13 mismatch trials, see Figures 1b and 1c. On both match and mismatch trials, the two pictures could depict the object from the same view or from different views rotated 90° in depth from each other. Except during practice, participants were given no feedback as to the correct response on a given trial. We expected participants to make many errors on similar (S1-S2 and S1-S3) mismatch trials. We were concerned that feedback on such trials might confuse or dishearten participants who may have been unable to detect a difference between the morphs on similar mismatch trials and who would not have understood why their responses were incorrect. Participants were not put under time pressure to respond as we wanted to determine their optimal performance in trying to achieve object constancy across a rotation in depth whilst discriminating between similarly shaped stimuli.

## 1.1 Method

### 1.1.1 Participants

Fifty-six participants volunteered to take part in the study. In this and the following studies, participants were undergraduate students from the University of Liverpool, U.K. who were naïve to the purpose of the study.

### 1.1.2 Materials

In this and the following experiments, thirty textured, shaded, three-dimensional models of familiar objects were individually morphed in varied and arbitrary ways to generate a set of thirty endpoint S1 morphs. The stimuli were modelled and rendered us-

ing the SoftImage (TM) animation software package. Each S1 shape was defined by a large number of polygons. For a given object, its S1 shape was morphed to produce an S13 morph. Morphing was achieved by deforming a lattice which was placed around S1. Deforming the lattice altered the position of the S1 polygon vertices which changed the shape of the object to produce S13. A further eleven morphs, S2 to S12, were produced by incrementally changing the S1 shape into the S13 shape by linear interpolation, see Figure 1a. This produced a total of 13 morphs of each object, labelled from S1 to S13, where S13 had the most dissimilar shape to S1. For each morph, grey-scale pictures of 12 different views were then produced by horizontally rotating the shape in depth. The (arbitrarily assigned front) foreshortened view was labelled as the 0° view. From this front foreshortened view, each successive view was rotated by 30° about the vertical axis running through the midpoint of the shape, and these views were labelled as 30°, 60°, 90°, 120°, and so on up to 330°. Altogether there were 156 pictures (thirteen morphs, each depicted from twelve views) of each of the thirty objects. The stimuli were presented against a black background inside a window measuring 450mm by 450mm on the computer screen.

In Experiment 1, 28 objects were presented in the experimental trials and the remaining two objects were presented in the practice trials. Each object was represented by six morphed versions, S1, S2, S3, S5, S7 and S13. Each morph was, in turn, depicted by two views (30° and 120°) which were rotated by 90° in depth from each other, see Figure 1b and 1c. Thus twelve pictures of each object (six morphs by two views) were presented in Experiment 1.

### 1.1.3 Design

Fourteen participants were randomly allocated to each of four groups. Two groups were presented with Object Set 1 (comprising 14 of the novel objects) and two groups saw Object Set 2 (comprising the remaining 14 novel objects), with the left picture always being a 30° view of S1 for one of each of the two groups and a 120° view of S1 for the other group. All participants completed one block of 168 trials, of which 28 were match trials and 140 were mismatch trials. There were two match and ten mismatch trials for each of the 14 objects seen by a given group. The left picture on a trial was always the 30° view or the 120° view of S1. On match trials, the right picture also showed S1, which was depicted once at the same view as the left picture (either 30° or 120°) and once at a different view (either 120° or 30°) for each object. On mismatch trials, the right picture showed S2, S3, S5, S7 or S13, each of which was depicted once at the same view as the left picture (either 30° or 120°) and once

at a different view (either 120° or 30°) for each object. In both the practice and the experimental blocks, trials were presented in a different, random order for each participant.

#### 1.1.4 Apparatus and Procedure

The experiment was run on a Macintosh PowerPC G4 computer using the Psyscope version 1.2.5 experimental presentation software. On each trial, a central fixation point appeared for 350ms. Two pictures of morphs of the same novel object were then immediately presented to the left and right of fixation for 1500ms. Participants made an unspeeded decision as to whether the two simultaneously presented pictures showed the same shaped stimulus or two differently shaped stimuli by making an “m” or “z” key-press respectively. After the participant had responded, there was an intertrial interval of 1000ms. Participants were told to ignore any difference in the view at which the left and right stimuli were depicted and they were warned that on mismatch trials, the left and right pictures might depict two objects with very similar shapes, and so the task was extremely difficult. Participants received no feedback on the correct response for each trial.

Prior to starting the experimental block, all participants completed a block of 25 practice trials. The practice trials were identical to the experimental trials except that they presented morphs of two objects which were not used in the experimental block, participants received feedback on the correct response for each trial, and there were approximately equal numbers of match and mismatch trials.

#### 1.2 Results

In this and all the following studies, the results for by-participants and by-items analyses are reported using subscripts  $F_p$  and  $F_i$  respectively. The dependent measure was the percentage of trials on which “same” responses were made. On match trials, same responses were correct. On mismatch trials, same responses were incorrect and represent trials on which participants thought that two pictures of different morphs actually depicted the same morph.

ANOVAs were conducted on the percentage of same responses for both match and mismatch trials. There were two within-participants factors, View Change (whether the left and right pictures showed morphs from the same or from 90° different views) and Shape Change (whether the right picture showed the S1, S2, S3, S5, S7 or S13 morph; the left picture always showed the S1 morph). There were two between-participants factors, Object Set (1 or 2, depending on which set of 14 objects was presented to a given participant) and Left Picture View (30° or 120°). The latter

two counterbalancing factors of Object Set and Left Picture View were included in the analyses as they reduced variance but they were not of interest in this study, and so effects involving these factors are not reported here.

Shape Change was significant,  $F_p(5, 260) = 334.852, p < .001, F_i(5, 130) = 137.275, p < .001$ . Same morph responses decreased as the shape change between the left and right pictures increased, from 69.8% to 65.6%, 51.0%, 34.2%, 22.7% and 14.7% for S1, S2, S3, S5, S7 and S13 respectively. View Change was also significant,  $F_p(1, 52) = 121.131, p < .001, F_i(1, 26) = 55.003, p < .001$ , with more same morph responses (both correct and incorrect) on same view trials (50.1%) than on different view trials (35.9%).

Most importantly, the interaction of Shape Change x View Change was significant,  $F_p(5, 260) = 42.885, p < .001, F_i(5, 130) = 36.106, p < .001$ . Matching was highly view-sensitive when morphs were similar in shape and so difficult to discriminate, but was view-invariant when morphs were dissimilar in shape and so easy to discriminate, see Figure 2a. The difference between responses on same view and different view trials was largest for S1 (32.7%) match trials, less for S2 (27.0%) and S3 (19.9%) mismatch trials, and was small or eliminated for S5 (3.6%), S7 (-0.8%) and S13 (2.9%) mismatch trials.

The above by-participants and by-items analyses were repeated for each of the four participant groups separately. In all eight analyses, the main effects of Shape Change and View Change and the interaction of Shape Change x View Change were significant at  $p < .01$ . The pattern of the Shape Change x View Change interaction was the same in all cases, and so the interaction was replicated over different groups of both participants and items, as well as for two different left picture views.

Note that this interaction cannot be explained by simply assuming that participants have a bias to respond “same” on same view trials. A simple bias explanation would predict no effect of shape change. This was not what we observed. Furthermore, participants were increasingly likely to respond “same” on different view (as well as on same view) trials as the two morphs depicted on a trial became increasingly similar in shape. It might still be argued that the current results are due to a bias to respond “same” on same view trials, but that the bias is masked by a ceiling effect for performance on mismatch trials which presented dissimilarly shaped morphs. For example, even on same view trials there were only around 20% incorrect “same” responses for S1-S7 mismatches and just 10% same responses for S1-S13 mismatches, so arguably there was only limited room for improvement



on this performance for different view trials. Here, though, the results from S1-S5 mismatch trials are important. There were over 30% incorrect “same” responses on same view S1-S5 mismatch trials, so performance could have improved on this considerably for different view trials, yet here participants made over 30% incorrect “same” responses on different view trials.

We used signal detection theory to calculate the cumulative sensitivity of participants to shape changes (relative to the S1 morph in all cases) on same view and different view trials (Macmillan & Creelman, 1991). Cumulative sensitivity monotonically increased as the shape change between stimuli increased, and it was always greater on same view than on different view trials, see Figure 2b. Cumulative sensitivity was significantly greater than chance in all conditions ( $p < 0.05$ ) except when discriminating between S1 and S2 morphs on different view trials.

### 1.3 Discussion

The results from Experiment 1 indicate that in an unsped-up simultaneous picture matching task, participants could use view-invariant information to discriminate between morphs with dissimilar shapes. On S1-S5, S1-S7 and S1-S13 mismatch trials, performance was as accurate when the two morphs presented on a trial were depicted from the same view as when they were depicted from different views rotated by 90° in depth. This view-invariant performance was not simply a result of performance being at ceiling, as the percentage of incorrect “same” responses reduced from S1-S5 to S1-S7 to S1-S13 mismatches, see Figure 2.

In contrast, on trials presenting morphs with identical shapes (S1-S1 match trials) or similar shapes (S1-S2 and S1-S3 mismatch trials), participants were highly sensitive to the views of the morphs presented. When both morphs on a trial were depicted from the same view, participants were much more likely to correctly (on S1-S1 trials) or incorrectly (on S1-S2 and S1-S3 trials) respond that both pictures showed the same morph, relative to when the morphs were depicted from different views, see Figure 2a.

This for dissimilarly shaped morph trials, judgements of shape similarity were not influenced by whether the same or different views were depicted. In contrast, when pairs of similarly shaped morphs were depicted from the same rather than different views, they appeared more similar, and so were more likely to be categorised as having the same shape. Overall, in Experiment 1 view sensitivity increased as the shape change between two objects decreased. This finding confirmed our prediction which was based on studies that found that view-sensitivity to plane disorientation

increased when more visually similar objects had to be discriminated (Lawson & Jolicoeur, 1998, submitted). This result is evidence against Cutzu and Edelman’s (1998) proposal that the representation of similarity by the human visual system is independent of view.

These results were not an artefact of the ease of recognition of the particular views selected. A clear and significant same view advantage on S1-S1, S1-S2 and S1-S3 trials (and view-insensitive performance on S1-S5, S1-S7 and S1-S13 trials) was found for both 30°-30° and 120°-120° same view trials compared to 30°-120° different view trials. The results also generalised across two different sets of morph objects tested with separate groups of participants.

## 2 Experiment 2

In Experiment 1, in a simultaneous matching task, we found a strong interaction between the effects of view change and shape change. In Experiment 2, we attempted to replicate and to extend this result. We varied the size of the shape change by comparing matching of S1 morphs to S1, S3, S5, S7, S10 and S13 morphs. We varied the ease of achieving object constancy across three view changes involving 0°, 30° and 90° depth rotations, to investigate whether view-sensitivity occurred only when there were large (90°) depth rotations between the two pictures, as in Experiment 1, or whether view-sensitivity would extend to relatively small (30°) depth rotations. Finally, we compared view change and shape change effects on simultaneous matching, as in Experiment 1, relative to sequential matching.

In a sequential picture-picture matching task, participants must store an internal representation of the first picture shown in order to decide whether that picture matches the second picture. The internal representation of the first picture may not be as accurate or as detailed as the representations available in simultaneous matching. The memory load requirement is particularly low in an unsped-up simultaneous matching task such as that used in Experiment 1. Here, the participant could look back and forth repeatedly to compare across the two pictures, and could concentrate on the most likely areas of difference in shape between the stimuli. In contrast, in a sequential matching task, such strategic, problem-solving approach cannot be used. Our primary reason for studying sequential matching was that the task requirements are closer to those of everyday object recognition (in which an input stimulus must be compared to stored memories of previously seen objects) than for simultaneous matching (for which problem-solving strategies could be employed which would not typically be available in everyday viewing situations).

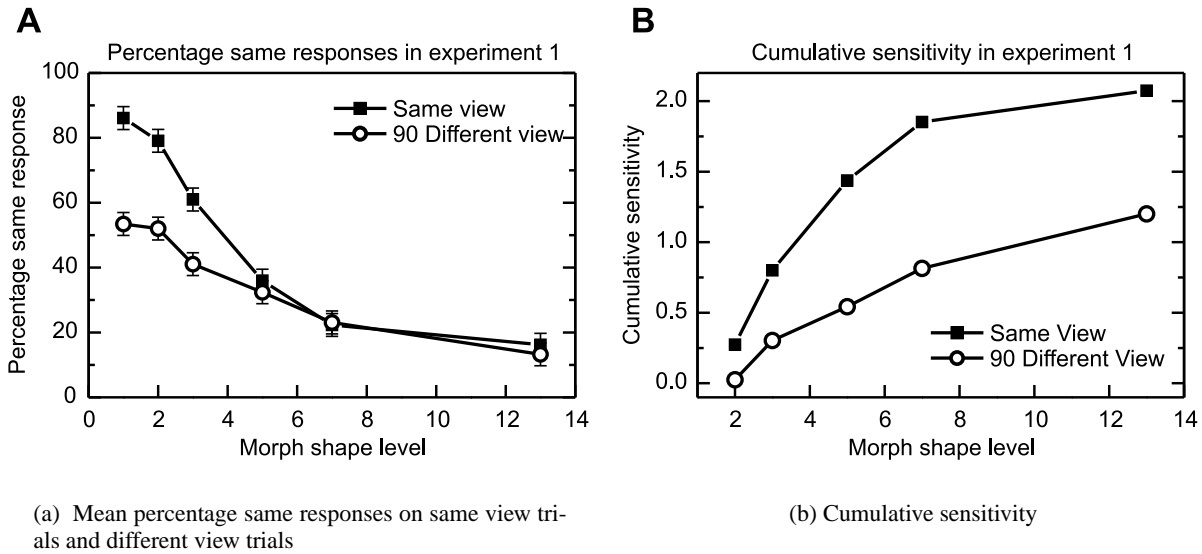


Figure 2: Results from Experiment 1: (a) mean percentage same responses on same view trials ( $0^\circ$  view change) and different view trials ( $90^\circ$  view change) when the morph of the right picture was S1 (match trials, where “same” shape was the correct response) or S2, S3, S5, S7 or S13 (all mismatch trials, where “same” shape was the wrong response) during simultaneous picture matching, along with 95% confidence intervals based on the error term for participants for the interaction of Shape Change x View Change (Loftus & Masson, 1994). On all trials, the left picture was the S1 morph; (b) the cumulative sensitivity,  $d'$ , of discriminating S1 from S2, S3, S5, S7 or S13 on same view and different view trials.

In Experiment 2, half the participants did the simultaneous matching task and half did the sequential matching task. As in Experiment 1, both pictures were presented for 1500ms in the simultaneous matching task. This provided sufficient time for participants to make several eye movements between the two stimuli. In the sequential matching task in Experiment 2, the left and right pictures were each presented individually for 1500ms. The total presentation time of the two pictures was therefore double in the sequential compared to the simultaneous matching task. This increased stimulus duration would be expected to improve performance in the sequential matching task, which would otherwise be expected to generally be more difficult than the simultaneous matching task.

In Experiment 1, participants were not given feedback as to the correct response on a trial and discrimination between the S1 and the S2 and S3 morphs was poor. Performance on S1-S7 and S1-S13 mismatch trials was relatively good, indicating that participants understood the task requirements. Nevertheless, participants may not have realised how poorly they were performing overall. To try to inform and to motivate participants to improve their performance in Experiment 2, we provided them with feedback throughout the study. In addition, we did not test mismatches with the

most visually similar pairs of morphs, S1 and S2 (instead we tested S10 visually dissimilar mismatches). Performance on S1-S2 trials was almost identical to that for S1-S1 match trials in Experiment 1, suggesting that participants could rarely discriminate between the S1 and S2 morphs. We did not wish to confuse participants by providing feedback that different morphs had been presented when the stimuli depicted were virtually indistinguishable.

In Experiment 1 there was only one match (same morph) trial to every five mismatch (different morph) trials. Since participants were receiving feedback in Experiment 2, they would be sensitive to the proportion of match and mismatch trials, and they may have been biased to respond different if most trials were mismatch trials. To avoid this, in Experiment 2 we increased the proportion of match trials to equal that of mismatch trials.

As in Experiment 1, the primary aim of Experiment 2 was to examine the nature of the relationship between shape changes and view changes. We predicted that view-sensitivity would increase as the difficulty of shape discrimination increased, when morph shapes were more similar.

## 2.1 Method

### 2.1.1 Participants

Twenty participants took part in the experiment for course credit.

### 2.1.2 Materials

Ten experimental and seven practice objects were used. The objects were a subset of those used in Experiment 1. Each object was represented by six morphed versions, S1, S3, S5, S7, S10 and S13. Each morph was, in turn, depicted by three views in depth, at 30°, 60° and 120°. In total, there were thus eighteen depictions of each object (six morphs by three views) presented in Experiment 2.

### 2.1.3 Design

Ten participants were randomly allocated to the simultaneous condition and ten to the sequential condition. On each trial, two pictures of an object were presented, one on the left and one on the right side of the screen. The pictures were presented either simultaneously, or sequentially with the left picture presented first. All participants completed 300 experimental trials, of which half were match and half were mismatch trials. These comprised 15 match and 15 mismatch trials for each of the 10 experimental objects. The left picture on a trial was always the 30° view of S1. On match trials, the right picture also showed S1, which was depicted at 30°, 60° and 120° views on five trials for each object. On mismatch trials, the right picture showed S3, S5, S7, S10 or S13, each of which was depicted once at 30°, once at 60° and once at 120° views for each object. In both the practice and the experimental blocks, the trials were presented in a different, random order for each participant.

### 2.1.4 Apparatus and Procedure

This was similar to Experiment 1 except for the following details. In the simultaneous matching task, stimulus presentation was as in Experiment 1. In the sequential matching task, the left picture appeared for 1500ms and was immediately replaced by the right picture which was also presented for 1500ms, with the pictures appearing in the same position as in the simultaneous matching task. In both tasks, after the pictures had been presented, participants saw a written prompt to respond, which reminded them of the m and z keypress responses for same shape (match) and different shape (mismatch) trials respectively. After making their response, participants were provided with feedback for 600ms which indicated the correct response for that trial. There was an intertrial interval of 500ms.

Prior to starting the experimental block, all participants completed a block of 14 practice trials. The

practice trials were identical to the experimental trials except that they presented morphed versions of seven objects which were not used in the experimental block, pictures were presented for 2500ms, the feedback was presented for 2000ms and the intertrial interval was 1000ms.

## 2.2 Results

ANOVAs were conducted separately on the mean percentage of same responses on match and mismatch trials since, unlike Experiment 1, there were five times more trials at each view for match than for mismatch trials. On match trials, there was one within-participants factor, View Change (the difference in view between the left and the right picture, 0°, 30° or 90°) and one between-participants factor, Presentation (simultaneous or sequential presentation of the left and right pictures). On mismatch trials, there were the same View Change and Presentation factors plus an additional within-participants factor, Shape Change (whether the right picture showed the S3, S5, S7, S10 or S13 morph; the left picture always showed the S1 morph).

### 2.2.1 Same shape match trials

View Change was significant,  $F_p(2, 36) = 82.585$ ,  $p < .001$ ,  $F_i(2, 18) = 15.417$ ,  $p < .001$ . There were over 20% more correct same responses on same view trials (95.2%) than on 30° or 90° different view trials (73.5% and 72.4% respectively). Presentation was not significant,  $F_p(1, 18) = 0.897$ ,  $p > .3$ ,  $F_i(1, 9) = 0.940$ ,  $p > .3$ . There were 81.8% correct same responses on simultaneous trials and 78.9% on sequential trials. Finally, the interaction of View Change x Presentation was not significant,  $F_p(2, 36) = 0.921$ ,  $p > 0.4$ ,  $F_i(2, 18) = 0.671$ ,  $p > 0.5$ , see Figure 3a and 3b. The increase in accuracy on same view relative to different view trials was similar across simultaneous (21.0%) and sequential (23.5%) picture presentation.

### 2.2.2 Different shape mismatch trials

Shape Change was significant,  $F_p(4, 72) = 211.373$ ,  $p < .001$ ,  $F_i(4, 36) = 39.856$ ,  $p < .001$ , with reduced errors as the shape change increased between the two pictures presented on a trial. There were 56.5%, 32.2%, 18.7%, 12.2% and just 6.7% incorrect same responses for S3, S5, S7, S10 and S13 mismatches respectively. View Change was not significant,  $F_p(2, 36) = 2.755$ ,  $p < .08$ ,  $F_i(2, 18) = 0.314$ ,  $p > .7$ . Same view trials did not produce more incorrect same responses. The marginal effect in the by-participants analysis was due to somewhat more errors occurring on 30° different view trials (22.7% incorrect same responses) than on either same view trials

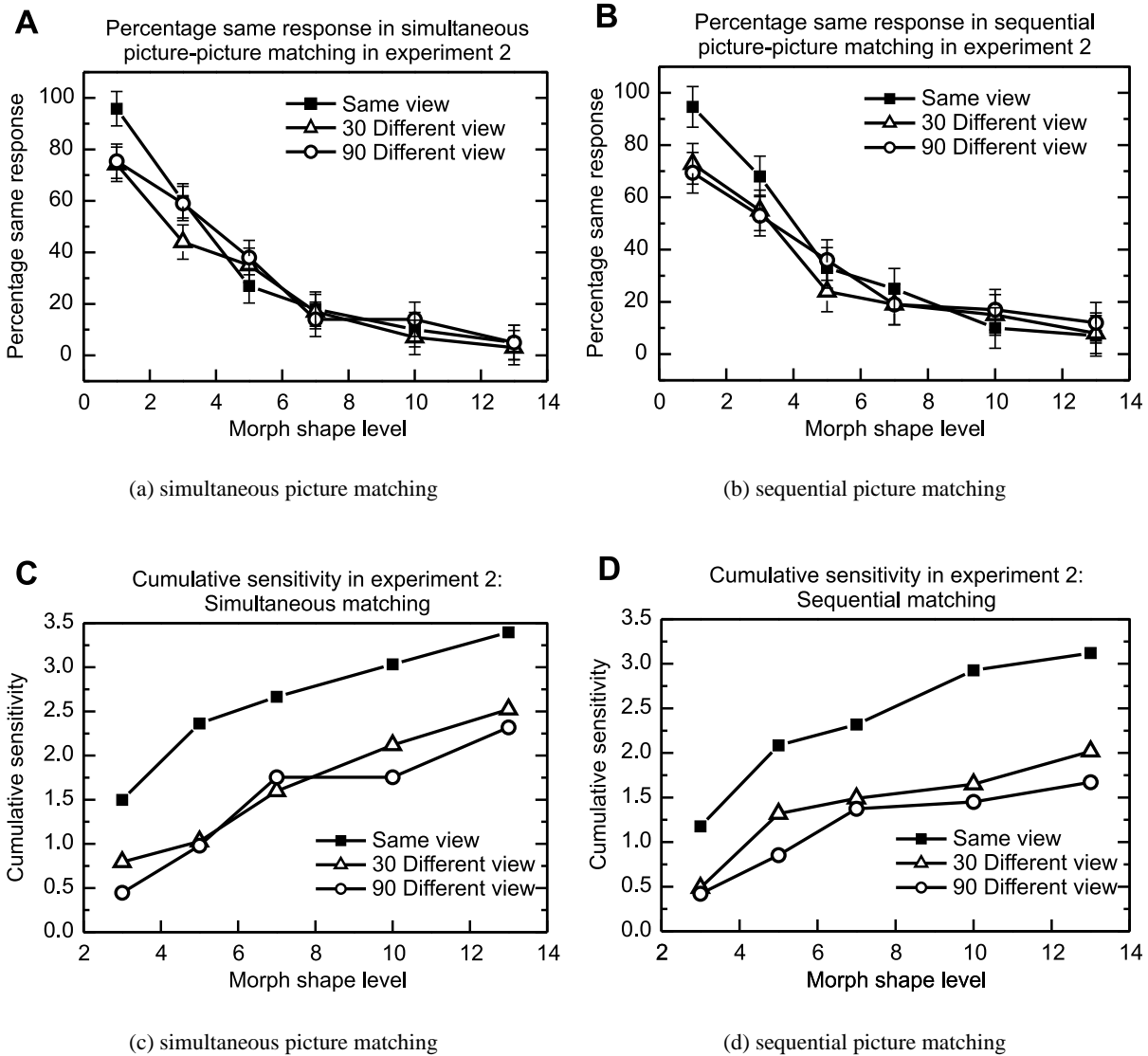


Figure 3: Results from Experiment 2: mean percentage same responses on same view ( $0^\circ$  view change) and different view ( $30^\circ$  or  $90^\circ$  view change) picture matching trials when the morph of the right picture was S1 (match trials, where “same” shape was the correct response) or S3, S5, S7, S10 or S13 (all mismatch trials, where “same” shape was the wrong response) during (a) simultaneous picture matching, and (b) sequential picture matching, along with 95% confidence intervals based on the error term for participants for the main effect of View Change for match trials and on the interaction of Shape Change x View Change for mismatch trials (Loftus & Masson, 1994). On all trials, the left picture was the S1 morph; also, the cumulative sensitivity,  $d'$ , of discriminating S1 from S3, S5, S7, S10 or S13 on same view or  $30^\circ$  or  $90^\circ$  different view trials during (c) simultaneous picture matching, and (d) sequential picture matching.

(26.3%) or 90° different view trials (26.7%). Presentation was not significant,  $F_p(1, 18) = 3.330, p > .09$ ,  $F_i(1, 9) = 2.118, p > .1$ , though as for match trials, there was a trend for better performance for simultaneous matching (23.7% incorrect same responses) than for sequential matching (26.7% incorrect same responses).

The only significant interaction was that of Shape Change x View Change, which was significant over participants but not items,  $F_p(8, 144) = 2.475, p < 0.02$ ,  $F_i(8, 72) = 1.527, p < 0.2$ , see Figures 3a and 3b. Only for S3 morphs was there a view change effect in the direction predicted. Here, around 11% more incorrect same responses were made on same view trials (64.0% same responses) than on 30° (49.5%) or 90° (56.0%) different view trials.

We used signal detection theory to calculate the cumulative sensitivity of participants to shape changes (relative to the S1 morph in all cases) on same view and different view trials. Cumulative sensitivity monotonically increased as the shape change between stimuli increased, and it was always greater on same view than on different view trials on both simultaneous and sequential trials, see Figures 3c and 3d respectively. Cumulative sensitivity was significantly greater than chance in all conditions ( $p < 0.05$ ).

### 2.3 Discussion

The results of Experiment 2 replicated and extended those of Experiment 1. For both simultaneous and sequential picture matching, performance was view-invariant when two visually dissimilar shapes (such as S1-S5, S1-S7, S1-S10 or S1-S13) were presented on mismatch trials. Here, matching accuracy was not improved when the two morphs were both shown at the same view rather than at different views. There was a clear effect of shape change with “same” responses systematically reducing across S1-5, S1-S7, S1-S10 and S1-S13 trials, but view change did not interact with this effect. In contrast, on S1-S1 match trials, performance was highly view-sensitive. When both pictures depicted S1 from the same view, there were over 20% more “same” responses than when 30° or 90° different views were shown. There was no difference between 30° and 90° different view match trials. A physically small view change (of just 30°) disrupted shape discrimination as much as a large (90°) view change, so the view change effects in Experiment 1 were not caused by the large rotations in depth tested. Finally, when two visually similar shapes (S1 and S3) were presented on mismatch trials, more “same” responses were made on same view than on different view trials. This effect mirrored, but was weaker than that for S1-S1 match trials. Overall, as in Experiment 1, there

was a systematic decrease in the influence of view on matching, from highly view-sensitive performance on S1-S1 match trials to moderate view-sensitivity on S1-S3 mismatch trials to view-invariance on S1-S5, 7, 10 and 13 mismatch trials.

Feedback seemed to improve overall performance in Experiment 2 relative to Experiment 1. For the simultaneous matching participants in Experiment 2 relative to the participants in Experiment 1, comparing same view and 90° different view trials, performance was more accurate on S1-S1, S1-S7 and S1-S13 trials, and was broadly similar on S1-S3 and S1-S5 trials, see Figures 2a and 3a. This was reflected in the greater cumulative sensitivity of participants in Experiment 2, comparing Figures 2b and 3c.

In Experiment 2, performance on mismatch trials was largely view-invariant. However, in Experiments 1 and 2, we may have underestimated the difficulty in achieving object constancy over depth rotation when visually similar shapes have to be discriminated, because an unspeeded response measure was used. Unspeeded tasks allow participants to use slow, problem-solving, view-invariant response strategies. Experiments 3 and 4 investigated sequential picture matching using speeded response tasks. Response times may provide a more sensitive measure of the interaction between view changes and shape changes. In addition, we extended our investigation of the importance of the temporal order of picture presentation by manipulating the interstimulus interval (ISI) between the two pictures presented on each sequential matching trial. Finally, we varied the experience of participants with the experimental stimuli prior to starting the matching task.

## 3 Experiment 3

In the speeded tasks of Experiment 3 and 4, we tried to replicate the interaction between shape change and view change effects which we had observed in the unspeeded tasks of Experiments 1 and 2. In Experiment 2, the size of the view change on different view trials (whether 30° or 90°) did not influence performance, so in Experiments 3 and 4 only one view change, 150°, was tested. Also, in Experiments 3 and 4, only S1-S1 match and S1-S7 mismatch trials were tested. The S1 and S7 morphs had sufficiently dissimilar shapes to have produced view-invariant performance on mismatch trials in both Experiments 1 and 2.

In Experiment 2, the simultaneous and sequential matching conditions produced very similar results. It is, though, difficult to make direct comparisons between sequential and simultaneous picture presentations because it is not clear how to equate the presentation duration of stimuli across the two conditions. To

avoid this problem, in Experiments 3 and 4 we only tested sequential picture matching, but we varied the ISI from 400ms to 1200ms to 3600ms (in contrast to the 0ms ISI used in sequential matching in Experiment 2). This ISI manipulation allowed us to investigate the effect of increasing the duration over which the internal representation of the first picture had to be maintained whilst fixing the presentation duration of the first picture at 500ms at all ISIs. The second picture was always presented until participants responded.

At longer ISIs, more information about the stimulus would be expected to be lost, so overall performance should be adversely affected. Furthermore, in some picture matching studies presenting familiar objects, view-sensitivity has been found to reduce at longer ISIs (e.g., Ellis & Allport, 1986; Lawson & Humphreys, 1996). Here, as ISI lengthens, participants may increasingly rely on a more abstract description of the first object shown, for instance by activating stored, view-invariant visual representations of the object, or an abstract semantic representation, or by accessing a verbal label for the object. This increasing reliance on more abstract information at longer ISIs may occur for novel as well as for familiar objects, particularly if participants are familiarised with the stimuli before the picture matching task begins. Familiarisation may allow participants to develop and store relatively view-insensitive, abstract visual, semantic or verbal representations of the objects. This was investigated by repeatedly showing stimuli to participants before starting the matching task in Experiment 3 but not in Experiment 4.

In Experiment 3, before starting the picture matching task, participants saw the 30° view of S1 for all the experimental objects in each of three blocks of training. In the first training block, participants were asked to rate the accuracy of a verbal description accompanying a picture of the S1 morph. In the second and third training blocks, participants had to try to recall the description whilst looking at the picture of the S1 morph, and they then had to rate the accuracy of their recall. These difficult memory and recall tasks were designed to make participants study the pictures and their descriptions carefully. In particular, we encouraged participants to attend to the three-dimensional structure of the objects by using verbal descriptions that emphasised the shape and relative position of the parts of the objects.

Recently, Walker, Dixon and Smith (2000) argued that pre-exposing participants to a novel name of a novel object (“This is a dax”) encourages “attention to be directed globally, at the overall configuration of a figure, ... because this allows the types of representation most supportive of object categorisation to be

encoded” (p. 621). These representations were assumed to be global 3D shape descriptions which are abstract and view-invariant, with privileged links to object names. They were contrasted to representations such as those derived from structurally impossible objects or derived under encoding conditions which do not emphasise 3D object shape as an important feature. Landau, Smith and Jones (1998) have also suggested that providing a name and describing a function for a visually presented novel object are both important factors in determining how adults generalise from a given object to new shapes. Together, this research suggests that providing names and functions for novel objects seen during an initial training phase can improve participants’ subsequent ability to achieve visual object constancy for those objects, by allowing view-invariant visual, semantic or verbal representations to be encoded. In contrast, Williams and Simons (2000) found no effect of learning to associate novel names with novel objects on participants’ subsequent ability to detect shape changes to those novel objects in a sequential matching task.

In Experiment 3, different verbal descriptions were shown to three different groups of participants:

- The real group read descriptions that explicitly named the original object from which a given morph was derived, and that linked its function to specific parts of the object. Descriptions started “This is a (machine gun) ...”, see Appendix 1.
- The like group read descriptions that named a novel object which the morph might be, and that linked its possible function to specific parts of the object. Descriptions started “This could be a (technologically advanced building machine) ...”.
- The part group read descriptions that made no reference to the name of an object or of any possible function of the object. Only the parts of the object and their spatial arrangement were described. Descriptions started “This object (has a long, complex, central horizontal section) ...”.

If participants could develop abstract, view-invariant representations of S1 morphs, then the real group were predicted to be the most likely to do so. Here, the description of S1 could usually be related directly to pre-existing abstract visual, semantic, functional and verbal representations of the familiar object which was specified in the description and from which the S1 morph had originally been derived. If such abstract representations were useful, then subsequent matching performance by the real

group should be good overall and relatively insensitive to view changes (see Walker et al, 2000; Landau et al, 1998). The part group was predicted to be least likely to develop abstract representations, since the verbal descriptions they were given did not include an object name or any semantic or functional information about the S1 morph. Indeed, the part group might instead develop a highly view-specific representation of S1, since they saw S1 repeatedly from the same 30° view and they were not encouraged to develop abstract, view-invariant representations. If so, then the part group might show even greater view-sensitivity than if they had had no training. Finally, the like group were given an object name and semantic and functional information which could be linked to the S1 morph, but this information could not usually be mapped to pre-existing, view-invariant representations. View-invariant representations should have been less readily accessible for matching for the like group than for the real group, but more accessible than for the part group. Thus the like group was predicted to reveal intermediate view-sensitivity relative to the real and the part groups.

### **3.1 Method**

#### **3.1.1 Participants**

Thirty-six participants took part in the study for course credit.

#### **3.1.2 Materials**

Eighteen experimental objects were used. The objects were a subset of those used in Experiment 1. Each object was represented by two morphed versions, S1 and S7. Each morph was, in turn, depicted by two views in depth, at 30° and 240°. In total, there were thus four depictions of each object (two morphs by two views). Real, like and part verbal descriptions of each of the 18 novel objects were also produced, see Appendix 1. The descriptions referred to the original object from which a given morph was derived and its function (real group), or a novel object which the morph could be and its possible function (like group), or made no reference to an actual object or function, and provided only visual rather than semantic or functional information (part group).

#### **3.1.3 Design**

Twelve participants were randomly allocated to each of the real, like and part groups. All participants completed three training blocks of 18 rating trials and one test block of 216 picture matching trials. The 30° view of the S1 morph of each of the 18 experimental objects was shown once in each training block. Each participant was presented with the same verbal description of a given object each time that they saw

that object during training. In the test block, each of the 18 objects were presented on six match trials and six mismatch trials. On all trials, the first picture presented was the 30° view of S1 which had been seen during training. The second picture was S1 on match trials and S7 on mismatch trials. On both match and mismatch trials, relative to the first picture, the second picture could depict the object from the same, 30° view (on three trials in the test block for each object, with an ISI of 400ms, 1200ms and of 3600ms) or from a different, 240° view (again, on three trials for each object, with an ISI of 400ms, 1200ms and of 3600ms). Prior to starting the experimental matching block, all participants completed a block of 20 practice trials. These practice trials were selected at random from the set of 216 trials used in the experimental matching block. In all blocks, trials were presented in a different, random order for each participant.

#### **3.1.4 Apparatus and Procedure**

The experiment was run on a Macintosh PowerPC G4 computer using the Psycscope version 1.2.5 experimental presentation software. In the first training block, participants first read a description of an object, then pressed the space bar. The 30° view of the S1 morph of the object that had been described was then presented. Participants made an unspeeded rating of the accuracy and informativeness of the object description, from 1 to 9. In the second and third training blocks, participants first saw the 30° view of the S1 morph of a given object. Whilst looking at the picture, they tried to remember the description of that object that they had read in the initial training block. They then pressed the space bar and the description that they had seen previously was presented. They re-read this description then made an unspeeded self-rating of their recall accuracy, from 1 to 9.

On each trial in the training blocks, a central fixation point appeared for 300ms and then was replaced by the object description in the first training block and the object picture in the second and third training blocks. When participants pressed the space bar, both the description and the picture appeared together. The picture was always presented at fixation and the description appeared centrally and above fixation. Both the description and the picture disappeared once the participant made a keypress to select a rating. There was an intertrial interval of 500ms. The descriptions and pictures were presented for an unlimited time and participants were not told to respond rapidly.

In the test block of picture matching trials, participants made a speeded decision as to whether two successive pictures showed the same or different objects. Participants made “m” or “z” keypresses to respond same or different respectively. On each trial, a central

fixation point appeared for 750ms, then after 500ms the first picture was presented for 500ms. After a blank ISI of 400ms, 1200ms or 3600ms, the second picture was presented until the participant responded. The first and second pictures were both presented at fixation. After a response was made, the correct response on that trial was given as feedback for 500ms, by presenting the letter m or z at fixation. There was an intertrial interval of 750ms. Participants were told to ignore any difference in the view depicted in the first and second pictures. They were warned that on mismatch trials, the pictures might depict two objects with very similar shapes, and so the task was extremely difficult. Participants were encouraged to respond as fast and as accurately as possible.

## 3.2 Results

Response latencies in picture matching trials less than 300 ms or exceeding 2300 ms were discarded as errors (less than 2% of trials). No participants were replaced. There was one missing cell in the by-items analyses which was replaced by the mean for that condition. ANOVAs were conducted on the mean correct matching RTs and on the percentage of “same” responses for match and mismatch trials separately. For all ANOVAs, there were two within-participants factors, View Change (same or different) and ISI (400, 1200 or 3600ms) and one between-participants factor, Condition (like, part or real training descriptions).

### 3.2.1 Same shape S1-S1 match trials

View Change was significant for both RTs,  $F_p(1, 33) = 237.904, p < .001, F_i(1, 17) = 200.064, p < .001$ , and errors,  $F_p(1, 33) = 280.882, p < .001, F_i(1, 17) = 57.547, p < .001$ . Same view matches (756ms, 93.2% correct same responses) were 322ms faster and 35.7% more accurate than different view matches (1078ms, 57.5%). ISI was also significant for both RTs,  $F_p(2, 66) = 19.961, p < .001, F_i(2, 34) = 20.570, p < .001$ , and errors,  $F_p(2, 66) = 6.858, p < .003, F_i(2, 34) = 4.518, p < .02$ . RTs slowed from 869ms to 922ms to 961ms, and correct same responses decreased from 76.9% to 76.5% to 72.4% as the ISI increased from 400ms to 1200ms to 3600ms respectively. Condition was significant only over items for RTs,  $F_p(2, 33) = 1.503, p > .2, F_i(2, 34) = 22.071, p < .001$  and was not significant for errors,  $F_p(2, 33) = 0.029, p > .9, F_i(2, 34) = 0.087, p > .9$ . The like group was slower (983ms) but no less accurate (75.6% correct same responses) than the real group (891ms, 74.9%) and the part group (877ms, 75.4%).

The interaction of View Change x ISI was significant for RTs,  $F_p(2, 66) = 7.759, p < .001, F_i(2, 34) = 8.225, p < .002$ , but not for errors,

$F_p(2, 66) = 0.487, p > .6, F_i(2, 34) = 0.397, p > .6$ , see Figure 4. For RTs, as the ISI increased from 400ms to 1200ms to 3600ms, same view responses increased markedly (from 676ms to 761ms to 831ms), whereas different view responses increased only modestly (from 1061ms to 1083ms to 1091ms). For ISIs of 400ms, 1200ms and 3600ms respectively, the decreased accuracy at the longest ISI was similar for same view trials (94.1%, 94.9% and 90.4% correct same responses) and different view trials (59.7%, 58.2% and 54.5%). Thus as ISI increased from 400ms to 1200ms to 3600ms, the benefit for same view over different view matches reduced but was far from eliminated for RTs (385ms to 322ms to 260ms), whilst the same view benefit for accuracy remained large (34.4% to 36.7% to 35.9%).

### 3.2.2 Different shape S1-S7 mismatch trials

View Change was significant for both RTs,  $F_p(1, 33) = 31.994, p < .001, F_i(1, 17) = 14.265, p < .002$ , and errors,  $F_p(1, 33) = 33.438, p < .001, F_i(1, 17) = 11.532, p < .004$ . Same view matches (928ms, 20.0% incorrect same responses) were 75ms faster and 12.1% more accurate than different view matches (1003ms, 32.1%). ISI was significant for both RTs,  $F_p(2, 66) = 7.661, p < .002, F_i(2, 34) = 5.292, p < .02$ , and errors,  $F_p(2, 66) = 7.266, p < .002, F_i(2, 34) = 7.062, p < .003$ . Performance was better for the shorter ISIs (400ms and 1200ms) than for the longest, 3600ms ISI for both RTs (949ms, 945ms and 1002ms respectively) and accuracy (24.2%, 25.0% and 29.0% incorrect same responses). Condition was significant only over items for RTs,  $F_p(2, 33) = 2.279, p > .1, F_i(2, 34) = 30.621, p < .001$ , and it was not significant for errors,  $F_p(2, 33) = 0.113, p > .8, F_i(2, 34) = 0.199, p > .8$ . As for match trials, the like group was somewhat slower (1044ms) but no less accurate (25.3% incorrect same responses) than the real group (942ms, 26.2%) or the part group (911ms, 26.6%).

The interaction of View Change x ISI was not significant for RTs,  $F_p(2, 66) = 0.273, p > .7, F_i(2, 34) = 1.326, p > .3$ , but it was for errors,  $F_p(2, 66) = 9.125, p < .001, F_i(2, 34) = 3.868, p < .04$ , see Figure 4. The increase in RTs at the longest ISI was similar for same view trials (906ms, 910ms and 968ms) and different view trials (993ms, 980ms and 1036ms) for ISIs of 400ms, 1200ms and 3600ms respectively. In contrast, whereas errors on same view trials increased with ISI from 15.1% to 19.6% to 25.3%, there was little effect of ISI on different view trials, with 33.2%, 30.4% and 32.7% errors for ISIs of 400ms, 1200ms and 3600ms respectively. Thus as ISI increased from 400ms, 1200ms and 3600ms, the benefit for same view over different view mismatches was relatively small



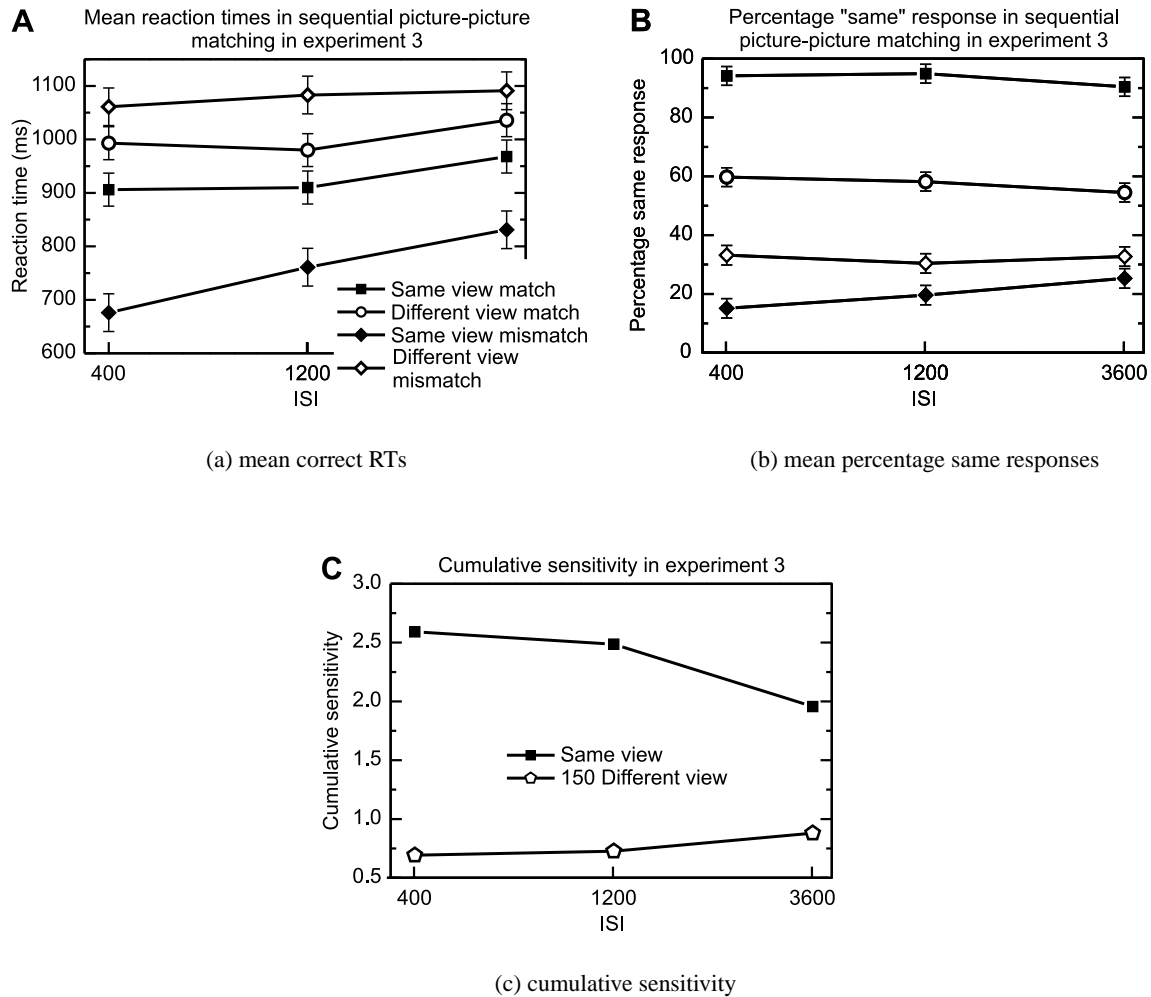


Figure 4: Results from Experiment 3: (a) mean correct RTs and (b) mean percentage same responses on same view ( $0^\circ$  view change) and different view ( $150^\circ$  view change) picture matching trials when the morph of the right picture was S1 (match trials, where “same” shape was the correct response) or S7 (mismatch trials, where “same” shape was the wrong response) during sequential picture matching, with an ISI of 400ms, 1200ms or 3600ms, along with 95% confidence intervals based on the error term for participants for the interaction of View Change x ISI for match and mismatch trials separately (Loftus & Masson, 1994). On all trials, the first picture was the S1 morph; also (c) the cumulative sensitivity,  $d'$ , of discriminating S1 from S7 on same view and different view trials at ISIs of 400ms, 1200ms or 3600ms.

and constant for RTs (87ms to 70ms to 68ms) whilst the same view benefit reduced markedly but was far from eliminated for errors (18.1% to 10.8% to 7.4%).

The only other significant interaction was for View Change x ISI x Condition for errors only,  $F_p(4, 66) = 3.131$ ,  $p < .02$ ,  $F_i(4, 68) = 2.360$ ,  $p < .07$ . Same view matches were more accurate than different view matches at every ISI for each group, and there was a larger same view advantage at the shortest compared to the longest ISI for all groups. The interaction was due to relatively small and unsystematic changes in the

size of the same view benefit at different ISIs across the three groups. Since these changes were not the focus of interest here, this interaction will not be considered further.

We used signal detection theory to calculate the cumulative sensitivity of participants to S1-S7 shape changes on same view and different view trials at ISIs of 400ms, 1200ms and 3600ms. Cumulative sensitivity was always much greater on same view than on different view trials. On same view trials, cumulative sensitivity reduced somewhat with increasing ISI

whereas on different view trials it was unaffected by ISI, see Figure 4. Cumulative sensitivity was significantly greater than chance in all conditions ( $p < 0.05$ ).

### 3.2.3 Match and mismatch error trials

Error rates are typically low (under 20%) in picture matching studies with speeded responses, since participants are usually encouraged to respond quickly but not at the expense of accuracy, as in Experiments 3 and 4 here. In Experiment 3, though, the task was difficult and the error rate was relatively high. We were therefore concerned that the results reported above for RTs for correct match and mismatch trials, though strong and reliable, might be misleading since so many errors were made. To investigate this issue, we divided the 36 participants in Experiment 3 into four equal groups on the basis of their overall error rate in the study. The groups had mean overall error rates of 19%, 24%, 27% and 31%. The above analyses were then repeated, except that a between-subjects factor of overall error rate (with four levels corresponding to the four groups of participants) was used instead of the Condition factor. The results replicated those reported above, with the same pattern of results being found for all four groups in all analyses. This suggests that the high error rates in this study did not distort the results reported above.

### 3.3 Discussion

In Experiment 3, participants were highly sensitive to view changes. Replicating and extending the results from the unspeeded tasks used in Experiments 1 and 2, performance on S1-S1 match trials was both faster and more accurate on same view than on different view trials. Performance on S1-S7 mismatch trials was also highly view-sensitive, with performance again being faster and more accurate on same view trials. This latter result contrasts to Experiments 1 and 2, where S1-S7 (and S1-S5, S1-S10 and S1-S13) mismatches were view-invariant. It also contrasts to S1-S2 and S1-S3 mismatches in Experiments 1 and 2, where accuracy was greater on different than on same view trials, due to a greater bias to say same shape on same view mismatch trials.

There are a number of possible explanations why in Experiment 3, unlike the previous studies, participants were more accurate (and faster) on mismatch as well as on match trials. For example, the use of a speeded task in Experiment 3 may have increased view-sensitivity by discouraging participants from using time-consuming, problem-solving view-invariant strategies to do the matching task. In addition, in Experiment 3 view-sensitivity on mismatch trials may have been increased by the initial training blocks in which participants repeatedly saw the 30° view of the S1 morphs. This 30° view training may have specifi-

cally benefited same view mismatch trials, since here both S1 and S7 were shown at 30° views. Experiment 4 tested this possibility by measuring whether a same view benefit still occurred when the training stage was omitted. Finally, the view change tested in Experiment 3 (150°) differed from those tested in Experiments 1 and 2 (30° and 90°), and it may have been particularly difficult to achieve object constancy over this view change. This seems unlikely, though, given that the views tested on 90° different view trials in Experiment 2 (120° views) and those tested on 150° different view trials in Experiment 3 (240° views) were mirror images of each other, see Figures 1b and 1c. Apart from a reflection, the same visual information would be available in both views and previous research has found little or no difference between picture-matching of identical and of mirror-image views (e.g. Lawson & Humphreys, 1996).

At longer ISIs, overall responses were somewhat slower and less accurate. ISI also interacted with view change, such that the same view benefit reduced at longer ISIs, see Figure 4. This interaction replicates those reported by Ellis and Allport (1986) and by Lawson and Humphreys (1996) in picture-picture matching studies presenting familiar objects. Note, though, that in Experiment 3 here, performance remained highly view-sensitive on mismatch trials and especially on match trials, even at the longest ISI.

The real, like and part groups tested in Experiment 3 produced very similar results. There was no evidence that the training to link pictures of the S1 morphs to descriptions giving names and functions for the morphs aided the real or like groups to develop view-invariant abstract descriptions of the morphs relative to the part group. This result is not consistent with the claims of Walker et al (2000) and Landau et al (1998) that learning names and functions for novel objects plays an important role in achieving object constancy. Instead, our results replicate Williams and Simons (2000) in finding no effect of learning names for novel objects on participants' subsequent sensitivity to detecting shape changes to those novel objects in a sequential matching task. It is, though, possible that the training in Experiment 3 influenced subsequent matching performance but that differences in the content of the verbal descriptions provided to the three groups were not important. This may, for example, have been because the important element of the descriptions was the emphasis on the global, parts-based structure of the object. This was provided in all of the real, like and part descriptions. In this case, we would predict reduced view-sensitivity following any training relative to if no training had occurred. Alternatively, the content of the descriptions may not have had any effect, but repeat-

edly seeing the 30° view of the S1 morph during training may have influenced subsequent matching performance. In this case, we would predict greater view-sensitivity (with faster and more accurate responses to 30° same view trials) following any training relative to if no training had occurred. These two alternative predictions were tested in Experiment 4, where participants received no training prior to the picture-matching task.

## 4 Experiment 4

In Experiment 4, we replicated Experiment 3 except that participants were not exposed to 30° views of S1 or to verbal descriptions of the objects in an initial training phase. The first block of picture-matching in Experiment 4 was identical to the block of picture-matching in Experiment 3. Comparing performance across these trials should indicate whether there was any influence of the training phase on subsequent matching performance.

In Experiment 4, we also examined the effects of practice by giving a second block of picture-matching trials to participants which was identical to the first block. After experience with stimuli during the first block of picture-matching, view-sensitivity may be reduced as participants encode and use more view-invariant representations of the morphs. Practise at the matching task may be more effective in reducing view sensitivity than the training blocks of pictures and verbal descriptions given in Experiment 3. The task was identical across the two blocks of picture-matching in Experiment 4 and both 30° and 240° views were presented in these picture-matching trials, whereas only the 30° view was shown during the description training in Experiment 3. A reduction in view change effects on match trials in the second relative to the first block of trials was reported by Lawson and Humphreys (1996) in a picture matching task which presented familiar objects. A similar influence of prior experience was predicted here.

### 4.1 Method

Twelve participants took part in the study for course credit. Experiment 4 was identical to Experiment 3 except that there were no training blocks and the test block of 216 matching trials was given to participants twice, with a self-timed break before the second experimental block.

### 4.2 Results

Response latencies in picture matching trials less than 300 ms or exceeding 2300 ms were discarded as errors (less than 2% of trials). No participants were replaced. ANOVAs were conducted on the mean cor-

rect matching RTs and on the percentage of “same” responses for match and mismatch trials separately. For all ANOVAs, there were three within-participants factors, View Change (same or different), ISI (400, 1200 or 3600ms) and Block (one or two).

#### 4.2.1 Same shape S1-S1 match trials

View Change was significant for both RTs,  $F_p(1, 11) = 96.103, p < .001, F_i(1, 17) = 162.947, p < .001$ , and errors,  $F_p(1, 11) = 88.049, p < .001, F_i(1, 17) = 45.656, p < .001$ . Same view matches (680ms, 94.3% correct same responses) were 273ms faster and 37.5% more accurate than different view matches (953ms, 56.8%). ISI was also significant for both RTs,  $F_p(2, 22) = 6.067, p < .009, F_i(2, 34) = 16.984, p < .001$ , and errors,  $F_p(2, 22) = 8.950, p < .002, F_i(2, 34) = 17.496, p < .001$ . RTs increased from 775ms to 819ms to 856ms and accuracy decreased from 78.0% to 77.0% to 71.6% correct same responses as the ISI increased from 400ms to 1200ms to 3600ms respectively. Block was significant for RTs,  $F_p(1, 11) = 18.003, p < .002, F_i(1, 17) = 58.158, p < .001$ , but not for errors,  $F_p(1, 11) = 0.415, p > .5, F_i(1, 17) = 0.391, p > .5$ . Responses in block 2 (772ms, 76.0% correct same responses) were 89ms faster but no more accurate than in block 1 (861ms, 75.1%).

The interaction of View Change x ISI was significant for RTs,  $F_p(2, 22) = 6.450, p < .007, F_i(2, 34) = 5.922, p < .007$ , but not for errors,  $F_p(2, 22) = 0.227, p > .7, F_i(2, 34) = 0.123, p > .8$ , see Figure 5. As the ISI increased from 400ms to 1200ms to 3600ms, RTs increased markedly on same view trials from 613ms to 675ms to 753ms, whereas RTs increased only modestly on different view trials from 937ms to 962ms to 958ms. The decrease in accuracy at the longest ISI was similar for same view trials (97.2%, 95.4% and 90.3% correct same responses) and different view trials (58.8%, 58.6% and 53.0%) for ISIs of 400ms, 1200ms and 3600ms respectively. Thus as ISI increased from 400ms to 1200ms to 3600ms, the benefit for same view over different view matches reduced but was far from eliminated for RTs (324ms to 287ms to 205ms), whilst the same view benefit for accuracy remained large (38.4% to 36.8% to 37.3%). This interaction fully replicated the results of Experiment 3.

The only other significant effect was the interaction of View Change x Block. This was significant for RTs,  $F_p(1, 11) = 17.708, p < .002, F_i(1, 17) = 15.654, p < .002$ , and marginally significant for errors,  $F_p(1, 11) = 3.443, p < .1, F_i(1, 17) = 3.368, p < .09$ . The advantage for same view over different view matches was greater in block 1 than in block 2. In block 1, same view matches (697ms, 95.1% cor-

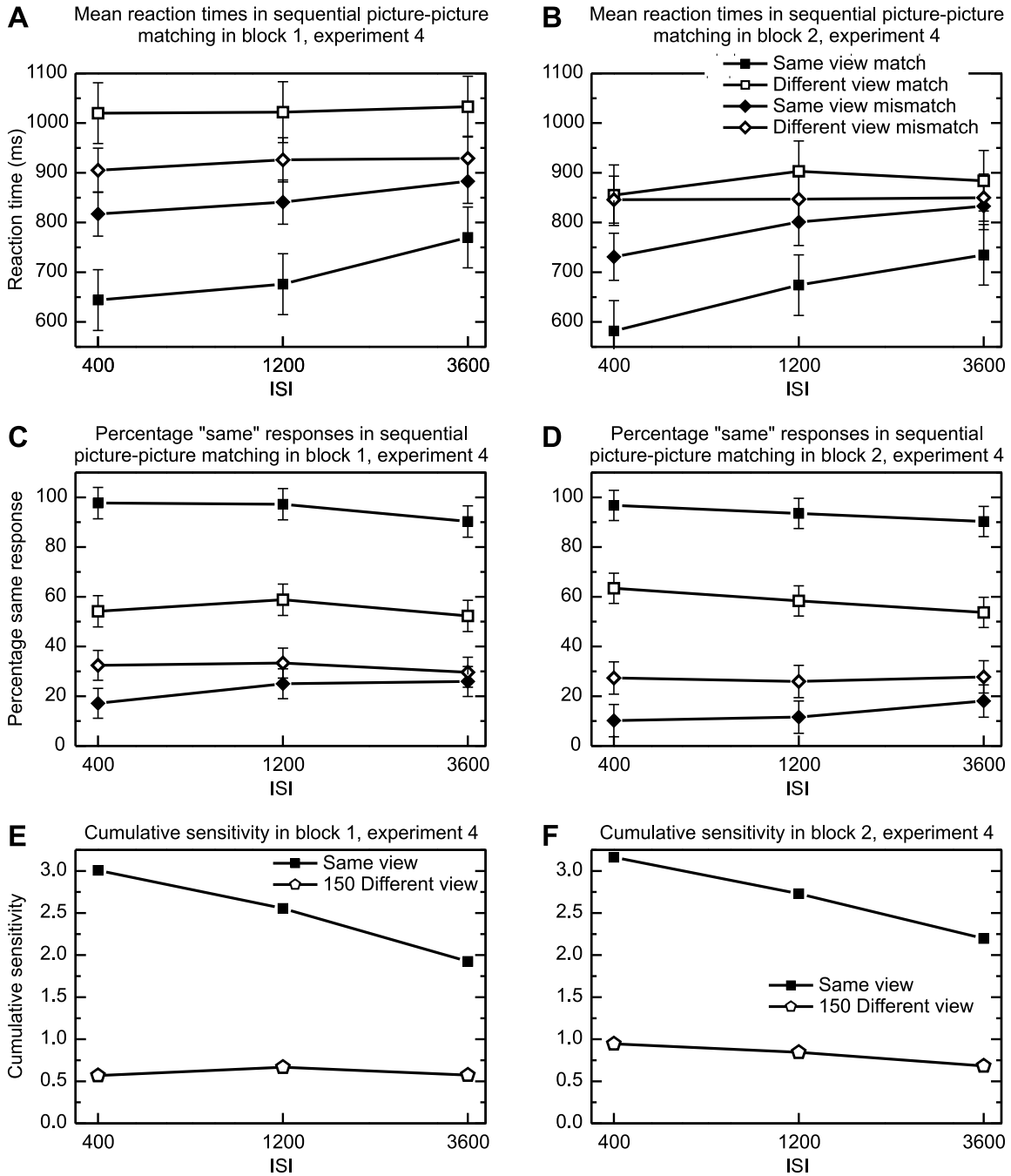


Figure 5: Results from Experiment 4: mean correct RTs in (a) block 1 and (b) block 2, and mean percentage same responses in (c) block 1 and (d) block 2, on same view ( $0^\circ$  view change) and different view ( $150^\circ$  view change) picture matching trials when the morph of the right picture was S1 (match trials, where "same" shape was the correct response) or S7 (mismatch trials, where "same" shape was the wrong response) during sequential picture matching, with an ISI of 400ms, 1200ms or 3600ms, along with 95% confidence intervals based on the error term for participants for the interaction of View Change  $\times$  ISI for match and mismatch trials separately (Loftus & Masson, 1994). On all trials, the first picture was the S1 morph; also, the cumulative sensitivity,  $d'$ , of discriminating S1 from S7 in (e) block 1 and (f) block 2 on same view and different view trials at ISIs of 400ms, 1200ms or 3600ms.

rect same responses) were 328ms faster and 40.0% more accurate than different view matches (1025ms, 55.1%). In block 2, same view matches (664ms, 93.5%) were 217ms faster and 35.0% more accurate than different view matches (881ms, 58.5%).

#### 4.2.2 Different shape S1-S7 mismatch trials

View Change was significant for both RTs,  $F_p(1, 11) = 13.441, p < .004, F_i(1, 17) = 8.525, p < .01$ , and errors,  $F_p(1, 11) = 9.878, p < .01, F_i(1, 17) = 11.248, p < .004$ . Same view matches (818ms, 18.0% incorrect same responses) were 66ms faster and 11.4% more accurate than different view matches (884ms, 29.4%). ISI was significant for RTs,  $F_p(2, 22) = 7.501, p < .004, F_i(2, 34) = 3.898, p < .03$ , and marginally significant for errors,  $F_p(2, 22) = 2.595, p < .1, F_i(2, 34) = 3.019, p < .07$ . RTs increased from 824ms to 854ms to 874ms and errors increased from 21.8% to 24.0% to 25.3% incorrect same responses as the ISI increased from 400ms to 1200ms to 3600ms respectively. Block was significant for both RTs,  $F_p(1, 11) = 9.158, p < .02, F_i(1, 17) = 10.398, p < .006$ , and errors,  $F_p(1, 11) = 31.201, p < .001, F_i(1, 17) = 12.693, p < .003$ . Responses in block 2 (818ms, 20.1% incorrect same responses) were 65ms faster and 6.1% more accurate than in block 1 (883ms, 27.2%).

The interaction of View Change x ISI was marginally significant for RTs,  $F_p(2, 22) = 2.942, p < .08, F_i(2, 34) = 2.756, p < .08$ , and significant over participants and marginally significant over items for errors,  $F_p(2, 22) = 3.472, p < .05, F_i(2, 34) = 2.891, p < .07$ , see Figure 5. As the ISI increased from 400ms to 1200ms to 3600ms, RTs increased on same view trials from 774ms to 821ms to 858ms and errors increased from 13.7% to 18.3% to 22.0%, whereas on different view trials there was little effect of ISI with RTs of 875ms, 886ms and 890ms and errors of 29.8%, 29.6% and 28.7%. Thus as ISI increased from 400ms to 1200ms to 3600ms, the benefit for same view over different view mismatches reduced but was not eliminated for RTs (101ms to 65ms to 32ms) and errors (16.1% to 11.3% to 6.7%). This interaction replicated the results of Experiment 3.

Unlike for the match trials, the interaction of View Change x Block was not significant, either for RTs,  $F_p(1, 11) = 0.242, p > .6, F_i(1, 17) = 0.132, p > .7$ , or for errors,  $F_p(1, 11) = 2.523, p > .1, F_i(1, 17) = 0.973, p > .3$ . The advantage for same view over different view matches was no greater in block 1 than in block 2. In block 1, same view matches (847ms, 22.7% incorrect same responses) were 73ms faster and 9.1% more accurate than different view matches (920ms, 31.8%). In block 2, same view matches (788ms,

13.3%) were 60ms faster and 13.7% more accurate than different view matches (848ms, 27.0%).

We used signal detection theory to calculate the cumulative sensitivity of participants to S1-S7 shape changes on same view and different view trials at ISIs of 400ms, 1200ms and 3600ms in block 1 and block 2. Replicating Experiment 3, in both blocks 1 and 2, cumulative sensitivity was always much greater on same view than on different view trials. On same view trials, cumulative sensitivity reduced somewhat with increasing ISI whereas on different view trials it was unaffected by ISI, see Figure 5. Cumulative sensitivity was significantly greater than chance in all conditions ( $p < 0.05$ ).

#### 4.2.3 Comparison of results from Experiment 3 and from block 1 only of Experiment 4

The following analyses were conducted in order to directly compare results from participants who were and who were not pre-exposed to pictures of the experimental objects during an initial training phase. Here, data from Experiment 3 (for the three groups of twelve participants who repeatedly saw pictures of the 30° view of S1 and verbal descriptions of the experimental objects during training, prior to starting the picture matching task) was analysed with the data from the first block of matching in Experiment 4 (for the group of twelve participants who saw no pictures or descriptions prior to starting the picture matching task). The analyses reported in Experiment 3 were then repeated, except that an additional level was included in the between-participants factor of Condition, to give a total of four levels for the four groups of participants tested, namely like, part, real or no training descriptions.

The main effect of Condition on RTs was marginally significant in the by-participants analysis and significant in the by-items analysis. This was because the like group were around 100ms slower than the other three groups on both match and mismatch trials. No other main effects or interactions involving the Condition factor were significant for either RTs or errors, in either the by-participants or the by-items analyses. The results of these latter analyses mirrored those reported above. Most importantly, there was no evidence to suggest that view-sensitivity varied across the like, part, real and no training groups. This suggests that the training received by participants in Experiment 3 did not influence their subsequent picture matching performance.

### 4.3 Discussion

The results of Experiment 4 replicated and extended those of Experiment 3. Both the speed and accuracy of responses were highly view-sensitive, with the same

view advantage being greater on S1-S1 match trials than on S1-S7 mismatch trials. The effect of ISI interacted with view change, such that the same view advantage reduced at longer ISIs, see Figure 5. This result replicated the interaction reported in Experiment 3 (see Figure 4) and is also consistent with the finding of reduced view-sensitivity at longer ISIs in picture-matching studies presenting familiar objects (e.g., Ellis & Allport, 1986; Lawson & Humphreys, 1996). Note, though, that as in Experiment 3, performance in Experiment 4 was still highly view-sensitive, even at the longest ISI.

Unlike Experiment 3, in Experiment 4 participants received no training prior to the matching trials and yet results were very similar to those of Experiment 3, so training was not responsible for the large view change effects observed in Experiment 3. Instead, it seems likely that the requirement of a speeded response in Experiments 3 and 4 increased the view-sensitivity of performance relative to Experiments 1 and 2. The results of Experiment 3 relative to those of Experiment 4 suggest that presenting pictures, verbal descriptions, names and semantic information about the morph stimuli during training had little effect on subsequent matching performance. In contrast, in Experiment 4 practise at the picture-matching task did improve performance in block 2 relative to block 1, particularly on different view trials, see Figure 5e and 5f. The pattern of results in block 2 mirrored those of block 1, but for S1-S1 match trials (though not for S1-S7 mismatch trials) view-sensitivity was significantly reduced. In block 1, same view matches were 328ms faster and 40.0% more accurate than different view matches, whilst in block 2, same view matches were 217ms faster and 35.0% more accurate than different view matches. This replicates the finding by Lawson and Humphreys (1996) of a reduced same view advantage on match trials in the second relative to the first block of picture matching trials. Note, though, that in Experiment 4 here, the effects of practice were relatively weak, with a clear same view benefit remaining in all conditions in block 2. Together the results from Experiments 3 and 4 suggest that view change effects are relatively impervious to the prior experience of participants with the experimental stimuli and the task. This indicates that it was difficult for participants to develop, store and then use abstract, view-invariant representations of the experimental stimuli used in the current studies, so performance was always highly view-sensitive.

## 5 General discussion

In four picture-matching studies, we found that view-sensitivity varied systematically with shape changes.

On match trials, when both pictures on a trial depicted identical shapes, performance was always highly view-sensitive, with responses being both faster and more accurate when stimuli were presented from the same view rather than from different views in depth. Performance was less view-sensitive on mismatch trials when pictures of two objects with visually similar shapes were depicted. Performance was view-invariant, with no difference between responses on same view and different view trials, when pictures of two objects with highly visually dissimilar shapes were presented. This interaction between the effects of shape changes and view changes on object recognition has often been assumed but has been difficult to test rigorously. The novel stimuli tested in the current studies were derived from a relatively large and diverse set of familiar objects which varied in complexity, global shape, number and spatial arrangement of parts, etc., and the results generalised across by-items as well as by-participants analyses. Shape changes were produced by incrementally morphing these novel objects. This allowed the ease of shape discrimination to be systematically manipulated. The findings reported here indicate how the human visual system achieves object constancy when similarly shaped objects need to be discriminated.

View-sensitivity was found reliably across a wide range of conditions: in both simultaneous matching (Experiments 1 and 2) and sequential matching (for ISIs from 0ms in Experiment 2 to 3600ms in Experiments 3 and 4); in speeded response tasks over both RTs and errors (Experiments 3 and 4) and in unspeeded response tasks (Experiments 1 and 2); whether provided with feedback (Experiments 2, 3 and 4) or not (Experiment 1); for a range of view changes (30°, 90° and 150°); with no prior training (Experiments 1 and 2 and block 1 of Experiment 4), after seeing pictures and verbal descriptions of the stimuli during training (Experiment 3), and after practice at the picture matching task (block 2 of Experiment 4). In all of these cases, matching pictures of visually similar shapes was highly view-sensitive, with significantly better performance on same view trials, whilst matching pictures of less visually similar shapes was significantly less view-sensitive. This interaction between shape change and view change was not greatly influenced by simultaneous versus sequential presentation (Experiment 2), size of view change (Experiment 2), ISI (Experiments 3 and 4), prior experience (Experiment 3) or practice (Experiment 4).

These results contrast to those of Cutzu and Edelman's (1998) sequential matching studies, which presented views of morphs all derived from a single animal-like object. As detailed in the introduction,

their results provided indirect evidence that the representation of similarity by the human visual system is independent of view. The current results are direct evidence against this hypothesis and instead suggest that view sensitivity is a robust phenomenon which is primarily influenced by shape change. The same view advantage in shape discrimination is both large and reliable across a range of testing conditions. The benefit in matching the same relative to different views of objects is systematically influenced by the similarity in shape of the objects whilst, conversely, the benefit in discriminating between dissimilar relative to similarly shaped objects is influenced by the view change between the objects. These findings demonstrate the pervasive importance of viewpoint, and the difficulty in achieving object constancy over depth rotation, for the human visual object recognition system.

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## Appendix

Object descriptions used in Experiment 3 for the object depicted in Figure 1c.

**Real group description:** This is a baseball catcher's helmet seen from below. The 'tongue' protruding forward protects the back of the neck. Above this are the two ear protector cages, on the right and the left side, as well as further metal bars to prevent skull injury. There is padded skull protection at the back and front.

**Like group description:** This could be a humane rat trap. The bait is placed inside the cage. The rat runs up the ramp which protrudes forward on the right side. This ramp springs up once the rat is in the cage. The metal catches at the top, left and right sides of the structure automatically click shut to lock the ramp in place to prevent escape. The padding at top and bottom prevents injury to the rat.

**Part group description:** This object is symmetrical and is hollow in the centre. At the front right is a flat, thin sheet which is angled downwards and is rounded at the far end. Behind and below the sheet is a dense, lumpy, hollow hemisphere. Above the hemisphere are a series of thin criss-crossing bars running horizontally and vertically. There is a second, smaller dense region above the central bars. Both the dense sections are surounded and topped by yet more thin bars.

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