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Domain-Specific Experience Determines Individual Differences in Holistic Processing

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Abstract

Holistic processing refers to the processing of objects as wholes rather than in a piecemeal, part-based fashion. Despite a suggested link between expertise and holistic processing, the role of experience in determining holistic processing of both faces and objects has been questioned. Here, we combine an individual differences approach with an experimental training study and parametrically manipulate experience with novel objects to examine the determinants of holistic processing. We also measure object recognition ability. Our results show that while domain-general visual ability is a predictor of the ability to match object parts, it is the amount of experience people have individuating objects of a category that determines the extent to which they process new objects of this category in a holistic manner. This work highlights the benefits of dissociating the influences of domain-general ability and domain-specific experience, typically confounded in measures of performance or "expertise". Our findings are consistent with recent work with faces showing that variability specific to experience is a better predictor of domain-specific effects than is variability in performance. We argue that individual differences in holistic processing arise from domain-specific experience and that these effects are related to similar effects of experience on other measures of selective attention.

Keywords: Face Perception, Object Recognition, Expertise, Individual Differences

Holistic processing refers to the processing of objects as wholes rather than in a piecemeal, part-based fashion. It was first described as a hallmark of face perception (Young, Hellawell, & Hay, 1987; Farah et al., 1998), after which it was reported as characteristic of expert processing with several non-face categories (Gauthier et al., 1998; Busey & Vanderkolk, 2005; Wong et al., 2011; Boggan, Bartlett, & Krawczyk, 2012). More recently, holistic processing has been obtained with non-face domains in novice observers (Tso et al., 2014; Zhao et al., 2016). Thus, despite the suggested link between expertise and holistic processing, the role of experience in determining holistic processing of both faces and objects has been questioned (McKone et al., 2012; Rezlescu et al., 2017). Here, we investigate individual differences in holistic processing, using a combination of experimental and correlational methods to assess the extent to which experience with a category determines a subject's level of holistic processing.

Operationalizing holistic processing. Several tasks have been used to operationalize holistic processing, and while they are sometimes assumed to tap into the same processes (e.g., Duchaine & Yovel, 2008; McKone, Kanwisher & Duchaine, 2007), these measures often do not correlate with each other (Rezlescu et al., 2017), with different tasks tapping into different meanings of holistic (Richler et al. 2012). Here, we define holistic processing as failures of selective attention to parts of an object, a meaning operationalized in the composite paradigm, in which parts of different objects are combined and observers asked to make judgments about cued parts while ignoring other parts. This meaning differs, for instance, from a "whole is greater than the sum of the parts" meaning (Shen & Palmeri, 2015). Defining holistic processing as a failure of selective attention to parts is not by itself a statement about its underlying mechanisms, which remain debated (e.g., Chua et al., 2015; Von der Heide et al., 2018). Nonetheless, holistic processing indexed by congruency effects in the composite task (performance on cued parts as a function of whether the uncued parts given consistent information about identity) has several advantages over other measures. A meta-analysis found larger effect sizes for this effect than for the alignment of cued and uncued parts, perhaps the other most popular index of holistic processing (Richler & Gauthier, 2014). Also relative to the alignment effect, the congruency effect is less susceptible to response biases that confound both differences between subjects and between studies (Richler et al., 2011, Richler & Gauthier, 2014). In addition, while many tasks of holistic processing yield measurements with reliability so low that they are not useful to characterize individual differences (for instance, the part-whole paradigm, Sunday et al., 2017), the congruency effect has been operationalized in a test designed to increase the reliability of individual differences measurements (Richler, Floyd & Gauthier, 2014). Here we capitalize on our recent efforts to develop a version of this test with novel objects (Chua & Gauthier, submitted).

Limitations of real-world domains to study experience. Interest in holistic processing stems from its being a hallmark of face perception (Hole, 1994; Farah et al., 1998) but the role of experience in holistic processing can be difficult to assess in real world domains like faces. For example, while some work suggested that other-race faces, with which people have less experience, are processed less holistically (e.g., Michel et al., 2006), other studies have found other-race faces to be processed as holistically as same-race faces (Zhao et al., 2014; Harrison et al., 2014), or to require very little training to reach equivalent holistic processing (McKone, Brewer, MacPherson, Rhodes &

Hayward, 2007). The kind of experience may also matter, as suggested by work with art students showing that with increasing experience drawing faces, artists process faces less holistically (Zhou et al., 2012). Some experience with Chinese characters increases their holistic processing, but holistic effects are found to be more limited for very experienced writers (Tso, Au, & Hsiao, 2014). In real world domains, changes with experience can be complex and variance influences can be difficult to disentangle. For instance, social attitudes may change with experience with faces of other groups, and semantic access may change with experience with Chinese characters.

Another challenge evaluating the role of experience in holistic processing using faces stems from the possibility that most people may already have too much experience with faces for this factor to drive differences in holistic processing. That is, using the Vanderbilt Holistic Processing test with faces (VHPT-F, Richler, Floyd, & Gauthier, 2014), a variant of the composite paradigm designed explicitly to measure individual differences in holistic processing with more reliability than previous tasks (Ross et al., 2015). high-powered studies have found no correlation between holistic processing and face recognition ability (Richler, Floyd, & Gauthier, 2014, 2015; Verhallen et al., 2017). This is consistent with research using other operationalizations of holistic processing (Royer et al., 2015; Rezlescu et al., 2017). Thus, contrary to a common assumption (Duchaine & Nakayama, 2006; Richler, Cheung & Gauthier, 2011), the best face recognizers are not necessarily more holistic, but this result may have limited implications for the role of experience in holistic processing.

Manipulating experience with novel objects. Another line of argument against the idea that congruency effects in the composite task arise from experience comes from the claim that these effects tap into general, non-face specific mechanisms (Rezlescu et al., 2017). Congruency effects in the composite task have been argued to be poor measures of holistic processing for faces because they can be obtained with inverted faces (Richler, Mack, Palmeri & Gauthier, 2011), cars (Bukach et al., 2010) or words/characters (Wong et al., 2011). However, given that experience is a proposed source of holistic effects, congruency effects for any non-face category for which we have *some* experience are only problematic if one decides *a priori* against the experience account. Novel objects are most helpful in this context, by providing a non-face, zero-experience control condition. In the present work, we parametrically manipulate experience with such novel objects. Aside from special cases with shapes designed to engage particularly strong perceptual grouping and where even novices show holistic processing (Zhao et al., 2016, but see Curby et al., 2018), congruency effects in the composite task are consistently large for faces (Richler et al., 2014; 2015) and very small (or null) for non-face novel objects in novices (Gauthier and Tarr, 2002; Richler et al, 2011; Chua & Gauthier, submitted). However, holistic processing has been reportedly found in groups of participants trained to recognize novel objects (Wong et al., 2009; Chua, Richler, & Gauthier, 2015; Richler et al., in press).

Experience or domain general influences on variability in holistic processing. While experience individuating objects may be sufficient to result in some holistic processing, the source of individual differences in holistic processing remain unclear. One straightforward hypothesis is that the degree of experience individuating objects from a category predicts the degree of holistic processing. Another possibility is that some individuation experience is important for the *emergence* of holistic processing, but that the amount of experience with a category, does not determine *the variability* in this strategy *across people*. For instance, even in training studies in which all subjects receive the same amount of training with novel objects and an average increase in holistic processing is found, it can vary substantially across subjects, enough to correlate with changes in brain activity in face-selective areas (Wong et al., 2009). Put simply, some level of familiarity with a category may raise the intercept but not affect the slope of the function relating holistic processing and degree of experience. Instead, variability in other domain-general mechanisms may affect the selective attention required in the composite task and influence individual differences in holistic processing. In this project, by manipulating experience parametrically with three categories of novel objects, matching experience with two of them, we can assess whether the degree of experience accounts for the level of holistic processing, or whether some other domain-general factor drives individual differences.

Recent work suggests that individual differences in cognitive control mechanisms, such as those contributing to performance on other selective attention paradigms like Stroop and Flanker tasks, do not contribute to holistic processing of faces (Gauthier et al., 2018). Nonetheless, some have argued that congruency effects in the composite task measure the same cognitive control mechanisms responsible for congruency effects in task like the Stroop paradigm (Rossion, 2013). In addition, domain-general abilities other than cognitive control could also drive individual differences in holistic processing. Critically, if *any* domain-general ability drove variability in holistic processing, we would expect strong correlations across all categories, largely independent of the manipulation of experience. For this reason, our design includes providing subjects with *some* experience with three categories of objects, only two of which are matched in degree of experience.

Here, we combine experimental and correlational approaches (Cronbach, 1957) to investigate the factors that account for individual differences in holistic processing. We use proven training methods to parametrically manipulate experience and test its effect on holistic processing and we do so using novel objects to maximize our manipulation of experience. We use new tests designed to be sensitive to individual differences in holistic processing with novel objects (Chua & Gauthier, submitted). Unlike prior work with a single novel category, we manipulate experience and measure outcomes with three different kinds of novel objects, allowing us to investigate correlations in holistic processing across categories. The parametric manipulation of experience with all of the categories allows us to test the prediction that experience drives holistic processing. The measurement of holistic processing for three categories, two of which are matched, allows us to test whether individual differences in holistic processing is mainly driven by variability in experience (for the two matched categories), or is instead driven by domain-general factors that would result in holistic processing correlating across all categories. Finally, we measure individual differences in object recognition ability (Richler et al., 2017) to assess whether this factor predicts holistic processing, non-holistic part matching performance, or both.

Methods

The study was conducted in three parts. We first screened all participants for object recognition ability, using the Novel Object Memory Test (NOMT, Richler et al., 2017). Subjects outside of 2 standard deviations of the mean were excluded (to avoid floor or ceiling effects in learning) from the individuation training, which itself was followed by a post-training test session assessing part matching and holistic processing in the Vanderbilt Holistic Processing Test for Novel Objects (VHPT-NO; Chua & Gauthier, submitted) for each of the three trained novel object categories.

Participants

68 total individuals were tested in the NOMT screening, 50 were selected to participate (mean age = 22.4 years, SD = 4.4, 33 female). Seven participants were ineligible because they scored two standard deviations above standard means for adults (Richler et al., 2017). Two participants were eligible for the individuation training study but terminated the study early (both did three days of training). Another 9 participants completed the training but the VHPT post-test data was lost due to software problems, so a new set of 9 subjects was recruited to replace them.

Participants were randomly assigned to five training groups, with 10 subjects in each group. Sample size was limited by resources, given that each subject participated in 11.5 hours of testing, but our main analyses consist of correlations over the entire sample and with the consideration that for 80% power to observe a correlation of .4 (based on a correlation in a similar length training design, McGugin et al., 2017) at an alpha of .05 would require 44 participants. Participants were paid $15 an hour. The entirety of the study consisted of the pre-training screening (~30 minutes), 10 individuation training sessions (~1 hour each), and the post training tests (~1 hour). All procedures were approved by the local IRB and participants gave written consent before starting the study.

Stimuli

Novel objects from five novel categories were used, two categories for NOMTs (Ziggerins category 1 and asymmetrical Greebles; see Richler et al., 2017 for details) and three for training and testing (symmetrical Greebles, Ziggerins category 2, and Sheinbugs, Figure 1). From each category, images of up to 46 objects (in two views, approximately 20 deg apart) were used (number depended on group, see procedure) were used for training, and a non-overlapping set of 42 different objects were used in the VHPT-NO (Chua & Gauthier, submitted). All images were shown in greyscale.

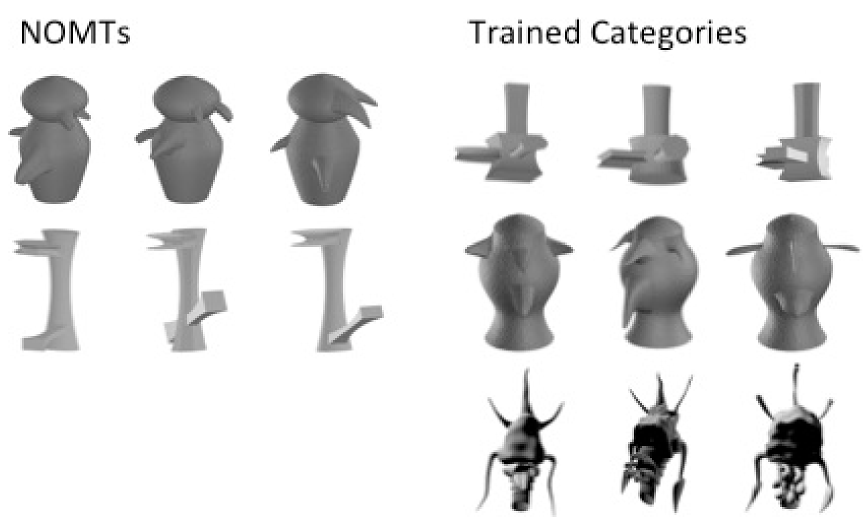

Figure 1. Examples of the two novel object categories (asymmetrical Greebles and Ziggerins category 1) used in the pre-test Novel Object Memory tests (Richler et al., 2017) and of the three categories (Ziggerins category 2, symmetrical Greebles and Sheinbugs) used in the training study.

Novel Object Matching Tests (NOMT)

Participants performed a prescreening test with novel objects, the Novel Object Memory Tests (NOMT, Richler et al., 2017), for two categories different from those in the training (asymmetric Greebles and Ziggerins category 1). The NOMT taps into a domain-general object recognition ability, as shown in a recent structural equation modeling study in which 89% of the variance in this and similar tasks was accounted for by a higher order factor, dissociable from general intelligence (Richler et al., in press). Details of the task are described elsewhere (Richler et al., 2017) and only summarized here. On each test, participants initially studied a set of six test objects, each one shown once in three different views followed by three-alternative forced choice trials in which they were asked to select the object they had previously viewed among distractors. This process was repeated for all six objects, after which all six learned objects are shown together for twenty seconds. In subsequent trials, participants saw one of the studied objects along with two distractors, and were asked to select the previously studied object. After 18 trials, participants were refreshed on the six memorized objects for another twenty seconds followed by another 36 trials, for a total of 54 test trials (72 trials total with the introductory phase). Object recognition ability was based on performance over all 144 trials ($\alpha = .83$).

Individuation Training

Each group received a different amount of training for three categories of novel objects. The total amount of training for each participant was constant (10 training sessions, each roughly one hour).

The training consisted of practice naming (using keypress) objects from three novel categories. Participants received an equal amount of training for two of the categories (varying in each group), and the remainder of a 10 hours allotment for a third category (Table 1). In addition to the time trained, groups differed in the number of exemplars and foils encountered, with higher amounts of time associated with more exemplars. Experience level is therefore operationalized as a fully confounded combination of training time and number of objects in the learning set. This was done because we are not interested in dissociating different aspects of experience, but rather bring under experimental control the ecological variability of experience that may exist for many real categories, whereby for example, a bird expert would have spent more time looking at birds and would know more individual birds than a bird novice.

Group	Ziggerins (matched)	Greebles (matched)	Sheinbugs (remainder)
1	9% (4,6)	9% (4,6)	82% (20,26)
2	14% (6,8)	14% (6,8)	72% (18,22)
3	20% (8,12)	20% (8,12)	60% (14,18)
4	30% (10,14)	30% (10,14)	40% (12,16)
5	45% (12,16)	45% (12,16)	10% (4,6)

Table 1. Percentage of the 10 hours training devoted to each category in the five training groups (number of named exemplars, number of unnamed foils).

Before the study started, participants were instructed that they would be learning individual members from three novel categories of objects. They were told that they would see an object appear on screen and the task would be to name it by typing the first letter of its name. The individuation training included learning trials and practice trials (see Gauthier et al., 1998, Chua et al., 2015). On learning trials, participants viewed each novel object with its name. On practice trials, an object was shown without the name and participants were to type in the first letter of the object's name. Each object could be shown in one of two views, approximately 20 degrees apart. Following the training session was a testing phase with feedback where the previously seen objects appeared without labels. The task was the same as before, but participants were given feedback if they gave an incorrect answer. Unnamed foils were also included in the stimulus set, for which participants were instructed to respond in "n" for "no name". Each day of training consisted of 700 test trials total, split between the three categories according to proportions shown in Table 1. To reduce the discrepancy in difficulty of the training between categories in early sessions, participants learned half of the exemplars (and saw half of the foils) for the first five days of training. Starting on day 6, the entire set was used.

Vanderbilt Holistic Processing Test – Novel Objects (VHPT-NO)

Following training, participants performed a holistic processing test for each of the trained categories of novel objects using the VHPT-NO (Chua & Gauthier, submitted). The test was structured after the fashion of the VHPT-F (Richler, Floyd, & Gauthier, 2014), which is both more reliable to individual differences and more sensitive to average group effects than the standard composite task, but has been shown to tap into the same construct (Wang et al., 2016). A separate test was used for each of the three trained categories: Sheinbugs, Greebles, and Ziggerins.

Procedure

All images were composite images made from a primary object with one target segment replaced with the equivalent part from another object and surrounded by a red box. The target segment varied in size (top half, bottom half, top 1/3, bottom 1/3, top 2/3, bottom 2/3, isolated part). On each trial, a composite object was shown for study for 2 seconds, followed by a test display showing three composite objects (with the same size target segment), one of which contained the same target segment as that in the study object. Participants were instructed to choose, on each trial, which of the three test objects contained the target segment. The test and study objects could be shown in one of two views, the same two views used for objects show during individuation training.

There were four different kinds of trials: normal congruent and incongruent trials, and RISE congruent and incongruent trials. On congruent trials, the target and irrelevant parts belonging to the correct answer were the same at test as in the study item. For incongruent trials, the target part was paired with a distractor part from a different object at test (see Figure 2). RISE (Random Image Structure Evolution, Sadr & Sinha, 2004) trials were identical to these, except that the distractor parts of the object (outside the red box) was transformed using an algorithm that randomizes image components while retaining the low level attributes of the image such as luminance, contrast, and spatial frequency. Performance on RISE trials can be used as a control to ensure that holistic processing is specific to whole objects from the trained categories (we would not expect interference from these scrambled images, and to the extent that interference is present, it is regressed out of congruency effects).

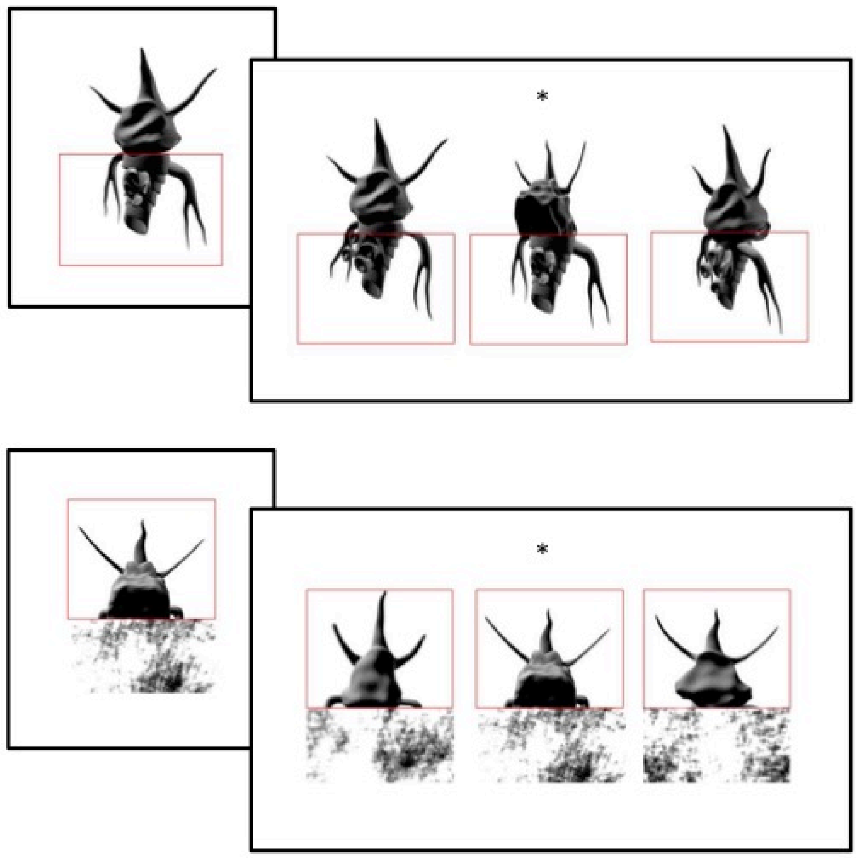

Figure 2. Example of trials from the VHPT-NO with Sheinbugs. The target segment varies in size and location but is indicated by a red box on each trial. Correct answers are marked with an asterisk only for illustration. On top is a normal trial in the incongruent condition because object parts outside of the red box for the correct answer do not match the studied composite. On the bottom is a RISE trial in the congruent condition, because the randomized image information outside of the red box for the correct answer matches the studied composite.

Two separate measures are computed for each subject using these trials. First, part matching performance can be computed over all trials, regardless of condition – this provides a measure of ability to match object parts, regardless of congruency. Second, a holistic processing score is computed by subtracting performance on incongruent trials from performance on congruent trials (in the normal conditions). Better performance on congruent than on incongruent trials indicates an inability to selectively attend (e.g., Richler & Gauthier, 2014; Richler et al., 2017). In addition, a congruency effect is computed for the RISE trials (performance on congruent – incongruent RISE trials) and this score is regressed out of the main congruency effect in all analyses to ensure there is no non-specific response interference that is not associated with whole objects. None of the analyses we report differ based on the inclusion of the RISE control, because, as can be appreciated in Figure 3, there are no substantial congruency effects at any point in the control condition.

Results

Novel Object Matching Test

Based on a previous sample (n = 672) tested on the same tasks (Richler et al., 2017), upper and lower boundary cutoffs were set at the 5^{th} and 95^{th} percentile. The final cutoffs for inclusion in the present study were combined scores above 81 and below 137 (out of 144). For the sample that went on to do the individuation training (n = 50), the mean combined score was 115, SD = 9.9. Participants were randomly assigned to groups, with no main effect of group on NOMT score, $F(4,45) = 0.87$, $p = 0.49$, $\eta_p^2 = 0.00$ – the extremely small effect size supports the idea that the groups are comparable in their visual ability.

Individuation Training

Participants improved over time in both accuracy and reaction time in the individuation task as they received more training (Supplemental Figure 1**)**. The amount of improvement in RTs and accuracy was significantly correlated with the amount of experience they received for each category (Supplemental Materials).

Tests of Holistic Processing

How does experience affect holistic processing?

After verifying that there was no difference in holistic processing for the two matched categories (Greebles and Ziggerins) with little evidence of an effect of Category, $F(1,45) = 1.18$, p = 0.87, $\eta^2 = 0.00$ or of a Category x Experience level interaction, $F(4,45) = 0.34$, p = 0.85, $\eta^2 = 0.01$, we averaged the results across those two categories to increase statistical power.

We tested for the effect of experience on holistic processing in an ANOVA using a linear contrast at the five different levels of experience, separately for the matched categories, as well as for Sheinbugs (with which levels of training varied to a greater extent). In both cases, we found that holistic processing increased with training (Figure 3). For Sheinbugs, the linear trend on experience level significantly predicted holistic processing, $b = 0.18$, $t(48) = 3.02$, $p = 0.004$, $R^2 = .16$. The same effect was also significant, although smaller, for the matched categories which received a smaller range of training, $b = 0.01$, $t(98) = 2.89$, $p = 0.005$, $R^2 = 0.08$. These effects were virtually unchanged if congruency effects in the RISE condition were controlled for.

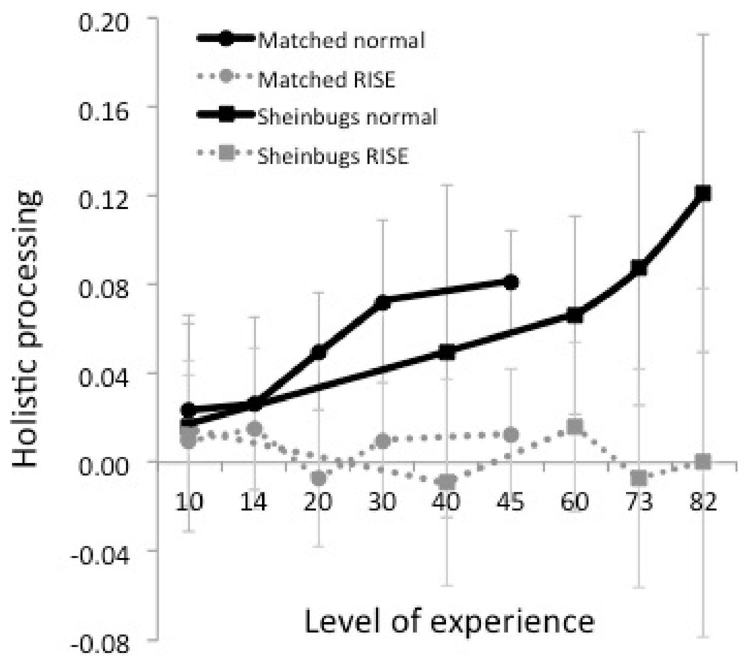

Figure 3. Holistic processing for the Sheinbugs and combined Greeble/Ziggerin categories (matched on experience level) as a function of level of experience (% of total training time for that category).

Correlational analyses

As in previous research (Richler et al., 2012; Ross et al., 2015, DeGutis et al., 2013), we calculated the reliability in each condition using Guttman lambda2, the reliability of the holistic processing difference scores on normal and RISE trials (Rogosa et al., 1982), and the reliability of the congruency effect in the normal condition, regressing out the congruency scores from the RISE condition (Malgady & Colon-Malgady, 1991). The resulting reliability of holistic residuals was .42 for Greebles, .46 for Sheinbugs and .43 for Ziggerins.

The matched categories (Greebles and Ziggerins) had equal experience levels for each participant, while the Sheinbugs had a level experience that was inversely related, across participants, to these matched categories. There was no significant correlation in holistic processing for the Sheinbugs and Ziggerins, r = -0.04, 95% CI [-0.24, 0.31], *t*(48) = -0.26, p = 0.80, or between Sheinbugs and Greebles, r = -0.24, 95% CI [-0.49, 0.04], *t*(48) = -1.68, p = 0.10. There was however a positive correlation in the amount of holistic processing observed across participants for Ziggerins and Greebles, r = 0.35, 95% CI [0.08, 0.57], t(48) = 2.56, p = 0.01 (Figure 4). The average correlation across categories (after fisher transform) was not significant (r = .03, 95% CI [-.25, .31], p=.42).

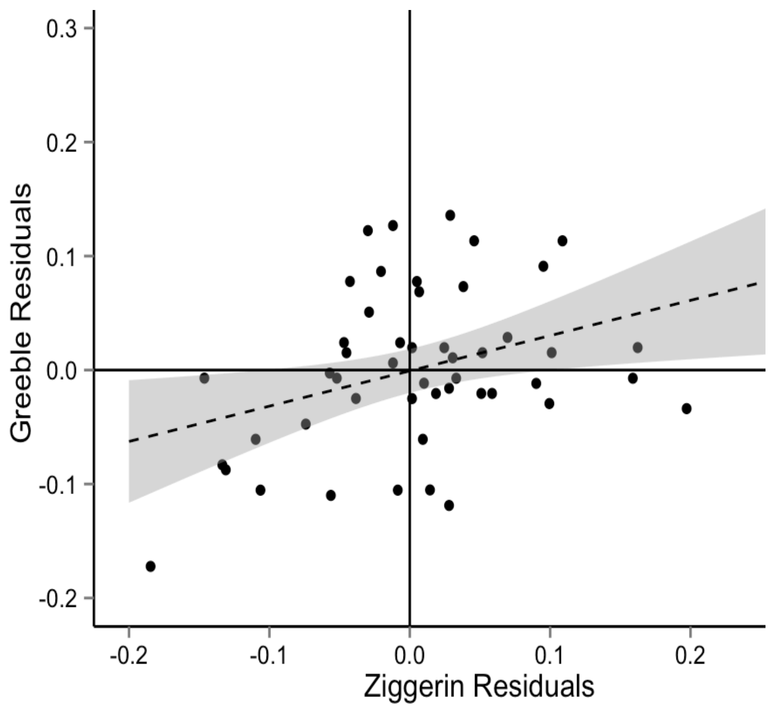

Figure 4. Correlation between holistic processing (residual scores) for Ziggerins and Greebles across trained participants, with 95% confidence interval.

Our experimental design was set up to explore the effects of experience on holistic processing. The range of visual ability as measured by the Novel Object Matching Tests was somewhat constrained excluding extreme performers (5%) on the high and low end, arbitrary cutoffs designed to reduce the possibility that our limited range in manipulation of experience would result in ceiling or floor effects in learning.

While our training groups did not differ in terms of overall visual ability, it is possible that, aside from experience, visual ability is also a predictor of the degree of holistic processing after training. In addition, we would expect that object recognition ability (NOMT scores) should predict non-holistic part matching performance in the VHPT-NO (as it does in novice observers, Chua & Gauthier, submitted). Finally, we can also ask whether experience is a predictor of part matching performance.

To that end, visual ability (NOMT score) and experience (manipulated) were entered into multiple regressions on holistic processing for each category. For all 3 categories, only visual ability was a significant predictor of part matching while experience level predicted the magnitude of holistic processing but did not predict part matching (see Table 2, Figure 5, Supplemental Figures). First-order correlations show the same result, with ability correlated with part matching (Sheinbugs r = 0.58, 95% CI [.36, .74]; Ziggerins r = 0.55, [.32, .72]; Greebles r = 0.67, [.48, .80]) but not with holistic processing (Sheinbugs r = 0.13, [-.15, .39]; Ziggerins, r = 0.04, [-.24, .31]; Greebles r = 0.09 [-.19,. 36]). In contrast, experience level was correlated with holistic processing (Sheinbugs r = 0.39, [.13, .60]; Ziggerins r = 0.29, [0.01, .53], Greebles r = 0.30, [0.02, .53]) but not with part matching (Sheinbugs r = 0.12, [-.16, .39]; Ziggerins r = -0.09, [-.36, .19]; Greebles r = 0.05 [-.23, .32]).

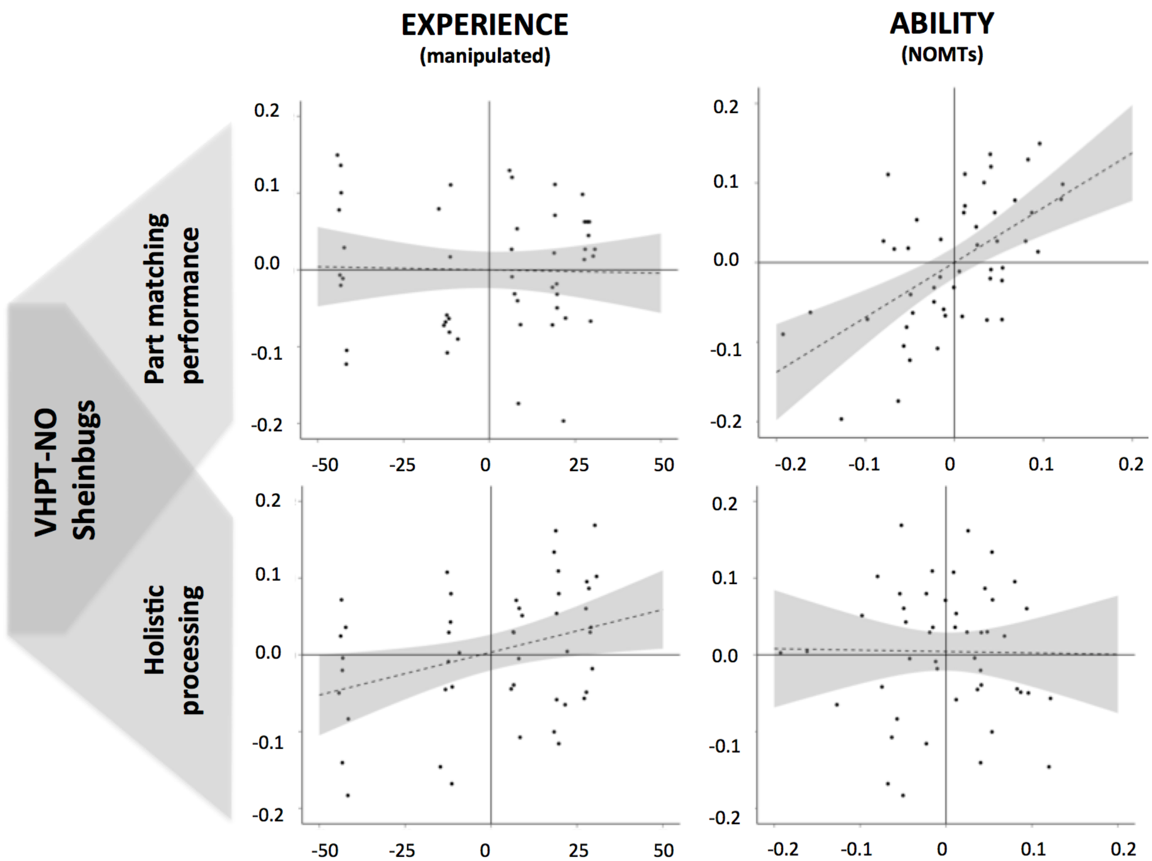

Figure 5. Partial correlations (residuals) between experience level and visual ability (on x-axes) for Sheinbugs, in each case controlling for the other predictor, and part matching and holistic processing (on y-axes). 95% confidence intervals shown.

	Sheinbugs part matching R-squared (adjusted) = 31.7%				Sheinbugs holistic processing R-squared (adjusted) = 13.0%			
	b	*se*	*t*	*p*	*b*	*se*	*t*	*p*
Constant	0.26	0.12	2.22	0.03	-0.190	0.142	1.33	0.19
Visual Ability	**0.69**	**0.14**	**4.81**	**0.00**	0.150	0.176	0.85	0.40
Experience Level	0.00	0.00	0.84	0.41	**0.000**	**0.001**	**2.87**	**0.01**
	Ziggerins part matching R-squared (adjusted) = 28.3%				Ziggerins holistic processing R-squared (adjusted) = 4.6%			
	b	*se*	*t*	*p*	*b*	*se*	*t*	*p*
Constant	0.29	0.12	2.38	0.02	-0.08	0.14	-0.58	0.57
Visual Ability	**0.67**	**0.15**	**4.50**	**0.001**	0.05	0.18	0.26	0.79
Experience Level	0.00	0.00	-.639	0.53	**0.00**	**0.00**	**2.07**	**0.04**
	Greebles part matching R-squared (adjusted) = 42.4%				Greebles holistic processing R-squared (adjusted) = 5.4%			
	b	*se*	*t*	*p*	*b*	*se*	*t*	*p*
Constant	0.31	0.09	3.45	0.001	-0.11	0.12	-0.95	0.35
Visual Ability	**0.68**	**0.11**	**6.11**	**0.000**	0.09	0.14	0.64	0.52
Experience Level	0.00	0.00	0.32	0.75	**0.00**	**0.001**	**2.11**	**0.04**

Table 2. Multiple regressions for part matching in the VHPT and holistic processing with NOMT score (visual ability) and experience level for each category.

General Discussion

We considered three possible determinants of individual differences in holistic processing: 1) a domain-general factor, to the extent that it would lead to correlated holistic effects across all categories, 2) experience, which was parametrically manipulated, and 3) object recognition visual ability, indexed by the NOMTs.

We found no evidence that a domain-general mechanism determines the magnitude of holistic processing for novel objects. We measured holistic processing for different categories of novel objects in the same participants. Had we found a correlation across object categories, especially one that was not related to our manipulation of experience, we would not know what the mechanism is, only that it is domain-general. The absence of a correlation, within the limitations associated with null effects, argues against a linear influence from a broad range of domain-general processes (e.g., cognitive control, intelligence, grouping). In contrast, we found clear evidence that the amount of experience with a category predicts the magnitude of holistic processing - and accordingly, individual differences in holistic processing were correlated across the two categories for which variability in experience was matched across subjects. This reveals for the first time a parametric effect of experience on holistic processing, with more experience resulting in more failures of selective attention. Finally, we examined evidence of a relationship between object recognition memory ability and holistic processing. Consistent with our conclusion that there does not seem to be a domain-general influence driving holistic processing, we found no relationship between object recognition ability and holistic processing. Object recognition ability was, however, clearly related to non-holistic part matching. This last result was also observed in novices for novel objects (Chua and Gauthier, submitted), suggesting that this correlation does not require experience or variability in experience.

Our work can help reconcile lines of research on holistic recognition with faces and with objects, and strongly challenges several assertions made in recent work on the topic. This includes i) the usefulness of congruency effects in the composite task to measure face-like holistic processing, ii) the relevance of finding composite effects in children to understand the causes of holistic processing, and iii) the unexpected lack of correlation between composite effects for faces and face recognition ability.

We find clear evidence from individual differences against the idea that congruency effects in the composite task tap into general, non-face specific mechanisms (Rossion, 2013; Rezelescu et al., 2017). Such claims have been based on the fact that these effects can be obtained for inverted faces, faces of another races or categories like cars or words, but it can be difficult to know if the experience we have with these categories drives the holistic processing observed. We postulated that experience may indeed be important, given that congruency effects are not obtained with all non-face objects, and indeed are generally not found for novel objects. A meta-analysis of congruency effects in the composite task shows a large effect size for faces, with no indication of publication bias (η_p^2 = .32, Richler et al., 2014). In contrast, studies using the same task with novel objects in novices reveal extremely small effects (η_p^2 =.03 in Richler et al., 2011; ηp^2 = .00 in Chua et al., 2015). The VHPT-F (Richler et al., 2015), a version of the composite task adapted to provide more reliable measurements of individual differences in holistic processing for faces, finds even larger congruency effects for faces (e.g., η_p^2 = .79). The VHPT-NO used in this study was matched to the VHPT-F in task demands. Here again, effect sizes for novel objects in novices are so small they can be considered null (e.g., η_p^2 = .02, Chua & Gauthier, submitted). The results from this training study clearly show that the congruency effects in VHPT-NO grow from non-existent in novices to substantial, as a function of experience.

Finally, we and others have pondered the meaning of the lack of correlation between holistic processing in the composite task and face recognition ability (Richler et al., 2015; Rezlescu et al., 2017). Rezlescu et al. (2017) argue that not observing this correlation means the effect is "a hallmark of face-specific information but not a measure of the efficiency of face perception mechanisms." We agree with the latter part of the claim, also supported by our finding that individuals with more efficient object recognition do not end up processing objects more holistically after training. We however strongly disagree with the first part of the claim, that holistic processing is face-specific. Our work confirms prior demonstrations that holistic processing is not face-specific (Bukach et al., 2011, Wong et al., 2009; Chua, Richler, & Gauthier, 2015; Richler et al., in press), with experience causing holistic effects with objects from categories that vary widely in their geometry. We propose that the relationship between level of experience and holistic processing, present in objects and not with faces, can be explained by assuming that measurements of face recognition ability in the normal population do not capture much variability in *experience* with faces, likely because experience is very high across the board. Aside from extreme cases, such as very large differences in population density in one's hometown (Balas & Saville, 2015; Sunday et al., in press) experience with faces may be too high in most people for studies with a sample from the general population to be sensitive to its effects. A similar argument was recently made by Oruc et al. (2018), to explain why at low levels of experience with faces, such as with people with Autism, the processing of identity and expression are correlated, even though they are thought to be independent in typically developing controls. Variability in experience may contribute more strongly to performance when experience is relatively low (which is also the case for novel objects), but once experience is very high (as for faces in the general population), other influences become a larger source of variation. For instance, variability on the CFMT in normal adult samples has been found to reflect large genetic influences (Wilmer et al., 2010; Shakeshaft & Plomin, 2015).

While the present work was not designed to test the underlying mechanisms of holistic failures of selective attention, prior work with similar training suggests that holistic processing can arise as a function of learned attention to diagnostic parts, without requiring the creation of a holistic representation *per se* (Chua et al., 2015). With experience individuating objects that are similar, participants benefit from spatially distributed attention, accumulating evidence from different parts of the object until they can reach a decision threshold. Some have suggested that episode-specific selective attention procedures (here, spatially distributed attention) are stored with other contextual information during learning (Crump et al., 2008; Jacoby & Brooks, 1984). The retrieval of such instances (Logan, 1988) could be the basis for failures of selective attention in the composite task. In this framework, more experience can lead to the creation of more instances in memory, leading to stronger holistic processing. In contrast, individual differences driving the discrimination of object parts may stem not from the number of instances in memory, but from the sensitivity parameters of each instance (Nosofsky & Palmeri, 1997).

A general implication of our work is that our understanding of holistic processing has been limited by couching it as a face-specific mechanism (e.g., Robbins & Mckone, 2007; Rezlescu et al., 2017). Indeed, while the behavior may be specific to faces in many comparisons, the specificity could arise from high levels of experience rather than from a dedicated process, and, paradoxically, at such a high level of experience, individual differences may no longer be driven by experience. One of our conclusions is that individual differences in holistic face processing are not driven by variability in domain general processes such as those accounting for shared variance among different cognitive control tasks (Gauthier et al., 2018). But a different take on these findings is that the majority of individual differences on congruency tasks, including Stroop or Flanker tasks and the composite task with faces, is not shared but category specific. This finding is consistent with modern theories of cognitive control, which is thought to operate at multiple levels of processing (Egner, 2008; Bugg & Crump, 2012) including effects from domain-specific experience. Training studies in classic cognitive control tasks like the Stroop paradigm have demonstrated the role of experience in selective attention (Macleod & Dunbar, 1988; Macleod, 1998). It is therefore possible to abandon the assumption that holistic processing reflects a face-specific process, while acknowledging that holistic processing effects for any category are domain-specific. This may be crucially important for our ability to model the mechanisms underlying these effects. Domain-specific effects can arise from the interaction of general mechanisms (be they perceptual, memory or attention-based) with experience in specific domains (see Oruc et al., 2018 and Van Gulick et al., 2015, for similar arguments).

There are limitations to this study. First, the range of visual ability was restricted, which could limit the relationship between visual ability and holistic processing (although this range in ability was sufficient to detect a relationship with part matching). Second, the internal consistency of the congruency effects in the VHPT was limited (mean reliability = ~.46), a common challenge with difference scores (e.g., Ross et al., 2015). Although it is higher than standard versions of the composite task and sufficient to find correlations driven by experience, the low reliability could have led us to underestimate effect sizes. Third, we defined experience as a combination of training time and number of exemplars learned, because these effects are generally correlated in real-world experience. Future studies could isolate time, number and diversity of exemplars to determine which factor exerts more of an influence on holistic processing.

In summary, we found that experience predicts individual differences in holistic processing, with no evidence of an effect of object recognition ability or of other domain-general influences. While we account for only a small amount of variance in holistic processing, it is worth noting that this amount is about twice as large for Sheinbugs (R^2-adjusted: .13) as for Greebles and Ziggerins (.05), likely because our design varied experience for Sheinbugs to a larger extent. The magnitude of the congruency effect for novel objects in the condition where subjects received most training in the present study was .12 (SD = .06), compared to .18 (SD = .11) for faces in the VHPT-F (Chua & Gauthier, submitted). It is not clear how much experience is needed to achieve levels of holistic processing equivalent to what is observed with faces, but if ten hours of experience with a novel category lead to congruency effects more than half the size of those observed faces, it may not seem unreasonable to suggest that the entire effect for faces may be driven by experience. As such, while much has been made of the fact that composite effects are large in children 3 to 5 years of age (McKone et al., 2012), such effects could also plausibly be driven by experience. Both training studies and individual differences are relatively costly approaches that require multiple sessions and sufficient sample sizes. The present compromise of 50 participants trained for 10 hours each represents an investment much larger than the typical study in cognitive psychology. While future work could benefit from increasing both the sample size or the training duration, we believe efforts to improve the measurement of constructs like visual ability and holistic processing will be key in facilitating progress in this area.

Author Contributions

K.-W.Chua and I. Gauthier contributed to study design, analyses and writing the manuscript. Programming and data collection were performed by K.-W. Chua.

Open Practices Statement

The experiment in this article were not formally preregistered, but the design, predictions and analyses were approved before data collection as part of K.-W. Chua's dissertation proposal. The data are posted here: https://doi.org/10.6084/m9.figshare.7286282.v1

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