The Selective Action of Cfunc Control

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Abstract

According to relational frame theory Cfunc stimuli select which stimulus properties are transformed via derived stimulus relations. To date there has been no demonstration of the selective action of Cfunc control. We provide an analysis of the requirements for such a demonstration, and describe the results from four experiments employing a paradigm consistent with these requirements. We employed a paradigm based on virtual car races. The paradigm had two components: i) a sample racecar screen which showed the performance of a sample racecar, and used experimentally engineered symbols to communicate how the performance of each real racecar would compare with that of the sample racecar, and ii) a car race screen showing other racecars race. Two symbols were established as Crels for the relations of same and different, and two symbols were established as Cfuncs for the functional properties of speed and direction. The results from these experiments demonstrate Cfunc stimuli can select which functions transform via derived stimulus relations, a central component of relational frame theory. The study has implications for the study of relational responding in complex settings and for applied work aimed at refining repertoires of relational responding.

Keywords

contextual control, transformation of function, arbitrarily applicable relational responding, derived stimulus relations, relational frame theory

The concept of arbitrarily applicable relational responding was proposed to account for the behavioral impact of language and cognition from the behavior-analytic perspective propounded by relational frame theory (RFT: Hayes et al., 2001). Since the earliest writings on arbitrarily applicable relational responding (Hayes, 1991; Hayes & Hayes, 1989) it has been an axiom that relational responding is contextually controlled by two types of stimuli: Crels and Cfuncs. The kind of relation that is brought to bear between stimuli is specified by a Crel, while the stimulus function that transforms in accordance with this relation is specified by a Cfunc (Hayes, et al., 2001). Hayes and Hayes provided a simple and compelling argument for the necessity of Cfunc control in a relational account of psychological functioning: "A given stimulus always has many functions. If all functions of one stimulus transferred to another and vice versa, there would no longer be two separate psychological stimuli, by definition. Thus, which functions transfer must be under contextual control." (Hayes & Hayes, 1989, p. 170; see also Hayes et al., 2001, p. 32).

Despite the critical role played by Cfuncs in behavioral accounts of relational responding, the vast majority of the research effort inspired by these accounts has focused on the relational activities controlled by Crels (e.g., Dymond & Barnes, 1995; Hayes et al., 1991; Roche & Barnes, 1997). This is understandable given that the powerful concept of stimulus relations greatly expanded the scope of behavioral accounts in the domains of language and cognition (Barnes-Holmes et al., 2018). The allure of the stimulus relations specified by Crels has meant that in general researchers have focused on demonstrating transformations of stimulus functions via stimulus relations of various kinds. In basic research this has typically involved establishing a behavioral function for a stimulus, establishing a relationship between this stimulus and another stimulus, and then testing this second stimulus for a transformed behavioral function derived from the first stimulus.

Critically, studies of relational responding often employed stimuli for which only one function is explicitly experimentally engineered – the function that would be transformed via a stimulus relation (e.g., Dymond & Barnes, 1995; Hayes et al., 1991; Roche & Barnes, 1997). In such a situation, where a stimulus has one function and it is transferred to another stimulus, observing the predicted transformation of function allows one to infer the impact of the stimulus relation specified by a Crel. However, studies of this kind do not allow one to infer directly the influence of a Cfunc, because these studies did not employ a stimulus to select which functions transformed between stimuli. Strictly speaking of course, the stimuli employed in these studies often did possess multiple functions. Consider that a successful demonstration of transformation of function requires that a stimulus relation is established. If stimulus relations are established between separate stimuli, it implies the stimuli being related have discriminative functions which differentiate them in the procedure employed to establish the stimulus relation (e.g., a matching to sample procedure). Thus, in studies where the transformed function was not the discriminative function differentiating the stimuli, the procedure must have involved the action of a Cfunc which specified that the non-discriminative function should be transformed from one stimulus to another. Note the indirect nature of the inference involved here. The lack of direct evidence for Cfunc action appears to be a function of researcher goals (i.e., engineering derived transformations of stimulus function). This has dictated the functions for which researchers have tested (i.e., the transformed stimulus functions), and the functions over which they sought to exert experimental control (i.e., Crels and not Cfuncs).

As described above, a major reason for the relative lack of research on Cfunc control was the justified research interest in Crel control. A second reason for the lack of basic research on Cfunc control is that demonstrating that a particular stimulus is exerting Cfunc control is not straightforward. There are several necessary components to such a demonstration. First, the stimulus from which the transformed function derives must have at least two functions. Imagine a hypothetical scenario involving a token that has a reinforcing function, and a Lego block that has no reinforcing functions. In an effort to establish a reinforcing function for the Lego block, an equivalence relation is established between the token and the Lego block, and the reinforcing functions of the Lego block are subsequently tested. If a source stimulus has only one function (e.g., the token) and that function is transformed to another stimulus, observing that the second stimulus (e.g., the Lego block) comes to possess that function provides no evidence that this function that was transformed was specified by a Cfunc. On the other hand, if that function is not transformed to the second stimulus, the result could be explained by failure to establish a stimulus relation, in which case the result would be due to weak Crel control and not effective Cfunc control.

Second, at least two of the source stimulus functions must be relevant to the situation in which the function transformation is assessed. Otherwise, the absence of the influence of a given behavioral function at test may be attributed to the conditions of the testing context and not to the selective action of a Cfunc. To help illustrate this point, imagine again the token. The token may serve as a reinforcer in one context, and in another context may be discriminative for handing it over in exchange for access to sweets or toys. Also imagine that the token is established as equivalent to a Lego block, and we only test the functions of the Lego block in the context of exchange for access to preferred items. We could not conclude that we had observed the selective action of a Cfunc which specified that only this function transferred, because the structure of the test would not permit assessing whether the reinforcing function had also transferred.

Third, the Cfunc should be shown to specify the behavioral function in the context of at least two kinds of derived stimulus relations. This ensures that the designated Cfunc specifies the function that is transformed, and not, for example, that a single stimulus has functioned as both as a Crel and Cfunc. For instance, a relational response by an individual that transforms a reinforcing function from familiar currency coins to unfamiliar currency coins may be controlled by the words “same value”, as in the hypothetical statement “this silver coin has the same value as that copper coin”. In examining this behavioral event we might assume that the word “same” functioned as the Crel specifying the relationship between the coins, and that the word “value” functioned as the Cfunc specifying the reinforcing function. However, the putative Cfunc, the word “value”, may not function to specify a particular behavioral function in isolation, but might form part of a compound stimulus that controls the relational response (e.g., the words “same value” stated together). This uncertainty could be reduced if we observed that the word “value” specified the same function in the context of another stimulus relation. For instance, an individual showing a preference for accessing a nickel coin after being told “this nickel coin has more value than that copper coin”. Observing this would suggest that the word “value” functioned as a Cfunc in the context of an equivalence relation specified by a Crel in the form of the word “same”, and in the context of a comparative relation specified by another Crel taking the form of the word “more”. A single stimulus functioning as both a Crel and a Cfunc precludes behavioral control over the function transformation that might be achieved by presenting or removing an independent Cfunc stimulus. The fourth and final requirement is related to this issue of behavioral control: the precise function transformation specified by the Cfunc must occur when it is present and not when it is absent. This ensures that the stimulus identified as the Cfunc is indeed the effective Cfunc as claimed, and the function is not specified by some other element of the context. This form of AB testing is commonly used to assess discriminative and other functions.

We are aware of only one basic experimental study that clearly demonstrated the simultaneous dual action of Crels and Cfuncs. This demonstration is provided by Stewart et al. (2013). The initial phases of the experiment established stimuli that functioned as Crels and Cfuncs. The final phase of the experiment involved a matching to sample task. The sample and comparison stimuli were shape stimuli that contained dots. These stimuli differed in the type of shape, the number of shapes, as well as the number and size of the dots they contained. These stimuli could be related in terms of these four features, and the variance in these features across stimuli meant that each of the four features facilitated application of the relations same, more than and less than. In the matching to sample task participants were required to select the appropriate comparison(s) for each sample stimulus given the stimulus relation and stimulus feature specified by the Crel and Cfunc stimuli. For instance, if the stimulus relation specified was one of difference and the stimulus feature was number of dots, correct selections were the comparisons that differed from the sample stimulus in terms of the number of dots. Although this study provides an example of stimuli that specify the type of stimulus relation and stimulus feature along which two stimuli are related, it has its limitations. In this regard, it is worth noting that Stewart et al. (2013) did not present their work as an explicit demonstration of Cfunc control. Instead, they described their work as multiple contextual control over arbitrarily applicable relational responding. Technically the authors' description is accurate. The contextual control in their study specifies the relevant stimulus relation and stimulus function for correct selection amongst comparison stimuli. It could be argued that because the functions of the stimuli (i.e., the shapes, number of shapes, the number of dots and their size) were not altered by the action of Crels and Cfuncs, the study by Stewart et al. (2013) does not meet the strictest technical standard of what constitutes a demonstration of Cfunc control over function transformation. That is, the alteration of the functional properties of one of the stimuli being related via the dual action of Crels and Cfuncs. Nonetheless, the study by Stewart et al. provides what we regard as the best example of Cfunc control in the currently published literature. There are other studies arguably involving Cfunc control (e.g., Hayes et al., 1987), with the study by Perez et al. (2021) being the most recent. Studies of this kind involve transformations of two stimulus functions from one stimulus to another, and testing the second stimulus for both of these functions. In these studies, there was contextual control over function expression in the test context. The Cfuncs in these studies did not select which functions should be transformed in accordance with a derived stimulus relation. This is not the same as contextual control over the transformation of function itself.

To exert contextual control over the transformation of functions, we examined the selective action of Cfunc control in a manner that satisfies the requirements outlined above. The procedure involved source stimuli with two relevant functional properties, which could be transformed via two kinds of stimulus relation, the presence and absence of Cfunc stimuli, and a test context in which both functional properties were task relevant. A generalization test of the engineered Cfunc stimuli was conducted also. We present four experiments conducted using the same computer-based car race paradigm described briefly below (see the procedure section of Experiment 1 for a full description). Establishing Cfuncs via contingencies of reinforcement likely requires many opportunities to relationally respond in contexts where the transformation of stimulus properties specified by those Cfuncs may be assessed and differentially reinforced. The car race paradigm provides a recyclable format in which relational responses under appropriate Crel and Cfunc control are required for the delivery of programmed reinforcers. The paradigm therefore seems a suitable context for establishing Cfuncs relevant to the car race context, such as those specifying the properties of speed and direction. The focus on contextually relevant Cfuncs in the current paper is a byproduct of the apparent need for repeatability when investigating how Cfuncs may be established.

The properties of speed and direction are important in the context of a car race. The winning racecar goes in the correct direction and does so quicker than the other racecars. At the beginning of each trial of the car race paradigm, a sample racecar is presented in the middle of the screen, and a finish line is presented to the left or right of the screen. The sample racecar performance is shown. The sample racecar moves either to the left or to the right and does so quickly or slowly. Selection boxes are presented at the bottom of the screen. Within each selection box, the sample racecar is presented to the left, a racecar participating in the next race is presented to the right, and pairs of Crels and Cfuncs specifying how the speed and direction of the racecar is related to that of the sample racecar are presented between the racecars (e.g., same speed, different direction). Following selection of a racecar the car race is shown. The sample racecar does not participate in the car race. Participants are tasked with selecting as many winners as they can. Critically, the position of the finish line, the performance of the sample racecar, and the performance of the racecars that could be selected for each race varied across trials. Varying the elements across trials meant that success would not result from response strategies based on particular combinations of programmed Crels and Cfuncs, the performance of the sample racecar, or characteristics of the racecars that could be selected. In layman’s terms, success in the task could only be achieved by noting the position of the finish line, the performance of the sample racecar, inferring - based on the Crels and Cfuncs - how the performance of each racecar was related to that of the sample racecar, and selecting the winner following comparison of these inferred performances. Consistent selection of the winning racecar in this paradigm implies participants responded to the racecars as if the racecars would have the specified properties of speed and direction derived from the sample racecar, a task that requires both Crel and Cfunc control over the transformation of the functional properties of the racecars.[1]

Experiment 1

Method

Data for the experiments we report were collected online via Prolific Academic. Participants were paid £7.50. In each experiment, the pre-registered stopping rule was 20 participants completing Cfunc training and testing. Ethical approval for these studies was granted by the Ethics committee of the Faculty of Psychology and Educational Sciences at Ghent University. All materials, data and analysis scripts can be found on the open science framework https://osf.io/7gvna/.

Participants

51 participants (18 female, mean age = 34 years, *SD* = 11) began the experiment. Of these, 22 participants were exposed to Cfunc training and testing. Due to the high attrition rate, pre-registered exclusion criteria related to Crel training and testing were not applied.

Procedure

The procedure was designed to establish Crel and Cfunc functions for stimuli and assess their efficacy in specifying derived transformations of stimulus functions. The procedure can be decomposed into five phases: phase 1) establishing Crels for the relations of same and different; phase 2) testing Crels for the relations of same and different; phase 3) establishing selective action of Cfuncs for speed and direction on transformations of functions via relations of same and different; phase 4) testing the selective action of Crels and Cfuncs established in the previous phase; phase 5) testing for the generalization of the experimentally established Crels and Cfuncs. All measures were programmed in java script using lab.js (Henninger et al., 2019).

Phases 1 and 2: establishing and testing Crels. In phase 1 a matching to sample (MTS) procedure was employed to establish Crels for the relations of same and different. The MTS began with the instruction "In this task you will see a sequence of screens. On these screens you must respond by selecting either E or I on your keyboard. Learn how to respond accurately. Then respond as accurately as you can." Before each block of trials, they were instructed "Respond as accurately as you can. If your accuracy is less than 85% this phase

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[1] This paradigm was partly inspired by a test procedure described by Belisle et al. (2020). In Experiment 2 of their article, stimuli specifying "faster" and "slower" were tested in the context of two balls rolled at different speeds by the experimenter. In spite of many differences between their procedure and our own, the influence of this work should be acknowledged.

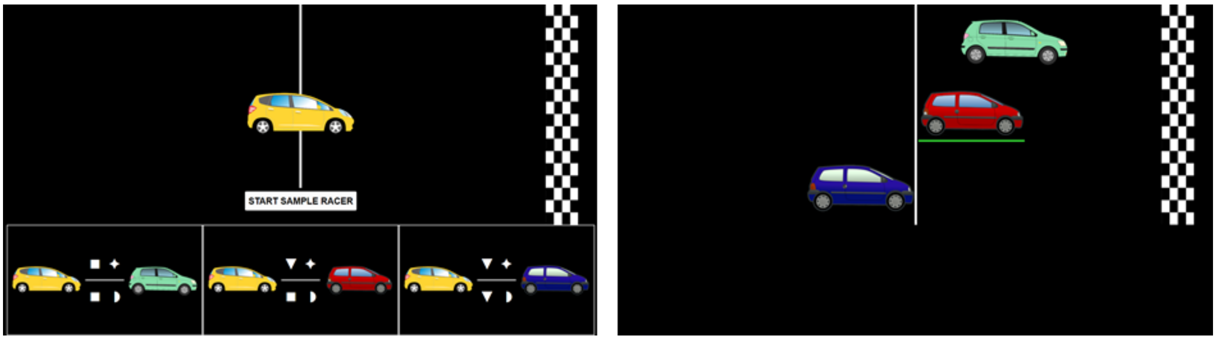
will begin again". Each trial began with a 300ms stimulus onset interval (SOI). The sample stimulus, the word "SAME" or "DIFFERENT", appeared at the top center of the screen, and the comparison stimuli, the symbols ■ and ▼, were presented at the bottom left and bottom right of the screen. Arbitrary shapes were established as Crels because this is standard practice in research on derived stimulus relations, and thus the experimental analysis reported here might complement and extend existing RFT-based experimental analyses of derived stimulus relations. The locations of the stimuli were counterbalanced across trials. Selections for the left and right comparisons were made with the 'E' and 'I' keys. Immediately after correct selections the message "Correct!" appeared in green text at the center of the screen for 500ms. The message "Wrong!" appeared in red text in the same location for 1000ms after incorrect responses. The MTS presented up to five 30 trial blocks, and terminated early if participants achieved an accuracy score ≥ 17/20 across the previous 20 trials in a block.

Phase 2 began after the MTS. The Crel properties of the symbols ■ and ▼ were tested in a delayed MTS used in a previous study (https://osf.io/w2n9g/). First, a Crel was presented for 1000 ms. After an SOI of 300 ms, participants were presented with an arrangement of three circles of equal size, two of which were the same color, that served as sample and comparison stimuli (e.g., a red circle at the top of the screen, a red circle at the bottom left, and a green circle at the bottom right). Participants received the instruction "Select the appropriately colored circle". They then selected a comparison stimulus after the presentation of each Crel (e.g., selecting the circle that is the same color as the circle at the top of the screen after seeing the Crel for same). No response feedback was provided during this 30-trial test block.

Phases 3, 4 and 5: establishing and testing Cfuncs. Phases 3 and 4 employed the car race paradigm. Each trial of the paradigm consisted of two parts, a sample racecar screen which is followed by the race screen. The layout of these components is shown in Figure 1. The sample racecar screen illustrated in the left panel of Figure 1 presented a sample racecar in the center of the screen, a finish line to the left or the right of the screen, and selection boxes at the bottom of the screen. Each selection box displayed the sample racecar on the left, a racecar on the right, as well as two pairs of Crels (i.e., ■ or ▼) and Cfuncs (i.e., ✦ or ◗) between the racecars. The selection boxes specified via the Crels and Cfuncs how each racecar would perform compared to the sample racecar. Within each selection box the Crels were always located to the left of the Cfuncs, but the Cfuncs for speed and direction were presented in the upper and lower positions within each selection box an approximately even number of times across trials. Five different racecar stimuli were presented across the task as a whole, with a maximum of four particular racecar stimuli being presented in a given trial (i.e., one sample racecar, and three racecars). The five racecar stimuli appeared equally often in each location throughout the study. This sample racecar screen also presented a white start line, and a checkered finish line. The white start line remained in a fixed location at the center of the screen. The finish line was presented at the same location on both screens within a trial, but appeared at the left and right of the screen an approximately equal number of times across trials. This manipulation ensured that the direction of the racecars was relevant to selecting the winning racecar.

Figure 1

An Example of a Trial from the Car Race Paradigm



Note. Screenshots of the sample racecar screen (left), and a screen shot of the race from the race screen (right) from the Cfunc training task that employed in Phases 3 and 4 of the experiment.

Clicking a button containing the text “start sample racecar” on the sample racecar screen showed participants how the sample racecar performed. In each trial the sample racecar moved to the left or right, and did so quickly or slowly. In trials where the sample racecar moved quickly it moved approximately 3 times faster than in trials when it moved slowly. Specifically, slow racecars were programmed to move 2 pixels every 1 ms, whereas fast racecars were programmed to move at a rate of 6 pixels every 1 ms. The performance of the sample racecar in conjunction with the combinations of Crels and Cfuncs could specify four different ways each racecar may perform relative to the sample racecar (i.e., same direction and same speed, same direction and different speed, different direction and same speed, or different direction and different speed). There was a maximum of three racecars that could be selected in each trial, so only three kinds of performances were possible. Table 1 below provides an overview of the ways the sample racecar could perform, and how the performances of possible winning racecars compared to the performance of the sample racecar. In this context it is important to bear in mind that the position of the finish line, the performance of the sample racecar relative to the finish line (i.e., whether it went in the correct direction), and the specified performance of the racecars were relevant to selecting the winning racecar on each trial. When participants made their selection, they progressed to the race screen where the racecar they selected was indicated by a green line (see right panel of Figure 1). During the race screen, the racecars moved across the screen either to the left or to the right and did so either quickly or slowly. After a race was completed, participants were informed whether they selected the appropriate racecar with the message “Your racecar won!” presented in green for 500ms or “Your racecar did not win!” presented in red for 1000 ms.

Table 1
An Overview of the Trial Types in the Car Race Paradigm

Sample racecar direction relative to finish line and speed	Winning racecar performances relative to sample racecar	
	Winner when available	Winning alternative
Correct direction and fast	Same direction and same speed	Same direction and different speed
Correct direction and slow	Same direction and different speed	Same direction and same speed
Incorrect direction and fast	Different direction and same speed	Different direction and different speed
Incorrect direction and slow	Different direction and different speed	Different direction and same speed

Note. This overview describes the ways the sample racecar could perform, and how the performances of possible winning racecars compared to the performance of the sample racecar. The ideal racecar would go quickly in the correct direction. The racecar described here as the “winner when available” would exhibit this kind of performance. However, a racecar that would go quickly in the correct direction was not provided as an option in every trial. Thus, the details of two possible winning racecars are provided because for some trials the racecar described here as the “winning alternative” was the optimal and correct choice. The possible winning performances are described here in relative terms, which represents the relations specified by the Crels and Cfuncs in the task. Note that due to the inter-trial changes in position of the finish line and performance of the sample racecar, across trials the winning racecar could exhibit any kind of performance; slowly to the left, slowly to the right, quickly to the left, or quickly to the right.

Phase 3 began with a brief walkthrough that oriented participants to the elements described above. The walkthrough, which lasted approximately two minutes, used text boxes and various animations to highlight the various features of the task. To proceed though the walkthrough participants used their mouse to select buttons within the textboxes or on other points of the screen. It began with the instruction:

> *In the next part of this study you will see racecars complete a number of car races. Before each race you will select the racecar you think will win the next race. To help you choose the winner of the next race you will be provided with some information about how each racecar will perform in the next race. Before you begin we will show you all the important parts of the task. Please read this information carefully.*

The walkthrough presented a screen like that shown in the left panel of Figure 1, along with the text "Before each race begins you will see a screen like this." After clicking continue an animation periodically altered the transparency of the sample racecar in the center of the screen and in the selection boxes, and the textbox text changed to "The sample racecar is at the center of the screen. At the bottom of the screen there are three boxes. In each box the sample racecar is presented to the left of three racecars." Clicking continue stopped the animation for the sample racecar, instead animating the racecars on the right of the selection boxes, and changed the text to "It is important to know that the sample racecar never participates in the next race. Only the racecars to the right of each box participate in the next race." Next, the symbols between the racecars were animated, and the text read "The symbols in the middle of each box indicate how the performance of each racecar compares to the sample racecar. The symbols presented here are just examples." After this the text informed participants

> T*he symbols tell you how the performance of each racecar compares to the sample racecar. The only way to predict the winning racecar is by understanding what the symbols tell you about how the performance of each racecar compares to the performance of the sample racecar. For this reason it is important to know how the sample racecar performs.*

At this point the text read "You can see the performance of the sample racecar by pressing the START SAMPLE RACECAR button." Clicking this button resulted in the sample racecar moving across the screen. Next participants were told "The performance of the sample racecar changes from race to race. To help you see the difference we will show you four sample racecars at the same time. In other parts of the study you will see only one sample racecar before a race." Continuing produced four sample racecars vertically aligned in the center of the screen, and the instruction "You can see the different ways the sample racecar might perform by pressing the START SAMPLE RACECAR button." Clicking the button showed all four possible movements of the sample racecars (i.e., moving quickly to the left, slowly to the left, quickly to the right, and slowly to the right). When the sample racecars reached the finish line the text read "Pressing the START SAMPLE RACECAR button again will allow you see the different performances once more. If you do not want to see the performances again, press the continue button below."

Pressing the Continue button began the sequence illustrating how the finish line would change locations. The text changed to "The performance of the sample racecar is not the only thing that will change from race to race". This sequence also showed four sample racecars of differing performances. The finish line began to the right of the screen, the text read "The finish line will sometimes appear on the right. The racecar at the top wins!" [fast to the right]. The four sample racecars were returned to the center of the screen, the finish line then moved to the left of the screen, and a new race commenced with the instruction "At other times the finish line will appear on the left. The racecar in the middle wins!" [fast to the left]. The walkthrough ended with the instruction

> *Now you have seen the important parts of this task: - the sample racecar and the different ways it might perform - the racecars that participate in the next race - the symbols that indicate how the racecars performances compare to the sample racecar - the changing location of the finish line. To continue to the race screen select a racecar by pressing the select button in one of the three boxes at the bottom of the screen.*

After this instruction participants progressed to the racecar screen (right panel of Figure 1), which showed the performance of the three racecars.

Phase 3 properly began upon completion of the walkthrough. In phase 3 participants were exposed to the training designed to establish the selective action of Cfuncs for the properties of speed and direction. The task instructions were:

> *Your goal is to select the winning racecar as often as you can. The performance of each racecar changes from race to race. The only way to predict the winning racecar is by understanding what the symbols tell you about how the performance of each racecar compares to the*

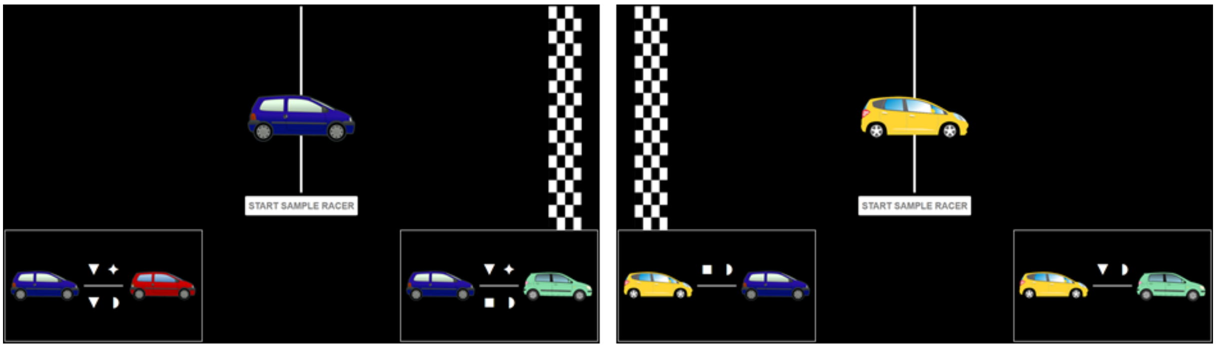
> *performance of the sample racecar. To select the winning racecar, pay attention to the sample racecar and the symbols in the boxes at the bottom of the screen. Use the information provided to select the winning racecar as often as you can. In the beginning this task will involve some trial and error. Please be patient and try your best to select the winning racecar. You will see in the race if you guessed correctly. To make sure you know whether you selected the winner, you will be told after each race if you selected the winning racecar. Good luck!*

Each block began with the instruction “Select as many winners as you can. If your accuracy is less than 85% this phase will begin again”. Participants were required to select the racecar they thought would win the next race. Blocks consisted of thirty races and terminated early if participants achieved an accuracy score ≥ 17 across the previous 20 trials within a block.

The Cfunc for direction was established before the Cfunc for speed. The programmed Cfuncs were the symbols ✦ and ◗, and the property each symbol specified (i.e., speed or direction) was counterbalanced across participants. Initially in phase 3 only two selection boxes appeared beneath the sample racecar (see left panel of Figure 2). When establishing the Cfunc for direction, the speed of the two racecars bore the same relation to the sample racecar. Thus, only the Cfunc for direction differed across racecars within trials and across trials within blocks. When establishing the Cfunc for speed, the direction of the two racecars was related to the sample racecar in the same way, and so only the Cfunc for speed varied across racecars and trials. Participants also received additional training trials in which the racecar stimuli varied along both Cfunc dimensions. This involved trials in which three selection boxes appeared beneath the sample racecar (see the left panel of Figure 1) and both the speed and direction of these three racecars varied within and across trials, and by extension so did their relationships to the properties of the sample racecar. Each of these three kinds of training just described (i.e., training for the Cfunc for direction, training for the Cfunc for speed, and mixed Cfunc training) lasted up to 5 blocks, terminating early when a participant met the training criterion. Phase 3 terminated when these three kinds of training blocks had been completed.

Figure 2

Two Illustrative Examples of Sample Racecar Screens Used to Establish Each Cfunc



Note. Screenshots of two illustrative sample racecar screens from training stages designed to establish a Cfunc for direction or speed. The selection boxes in the left panel present two programmed Crels and two programmed Cfuncs. Note that in the depicted trial the Crel and Cfunc pair in the upper portion of both selection boxes is the same. This was the format of the initial stages of Cfunc training in Experiment 1, 3, and later training stages of Cfunc training in Experiment 4. Selection boxes shown in the right panel present only one programmed Crel and one programmed Cfunc. This illustrates how Crels and Cfuncs were presented to participants in the initial stages of Cfunc training in Experiments 2 and 4.

The selective action of the experimentally established Crels and Cfuncs was tested in two ways. The first test comprised phase 4 of the experiment, and took the same format as the car race with three selection boxes described above, and simply involved the removal of the programmed consequences for two 30-trial blocks. After completing this, participants were shown the four symbols and asked to type their responses to the question "What do you think each of these symbols mean?". They were also provided a space to make other comments. Phase 5 of the experiment involved the second test of the established Crels and Cfuncs. This generalization test took a similar format to the final test employed by Stewart et al. (2013) which assessed Crel and Cfunc control over selection responses. The selection-based test assessed whether the established Crels and Cfuncs generalized to relations between new stimuli. The stimuli were two pictures each of a bicycle, a truck, a helicopter and a plane, one in which the vehicle was oriented to the left and one with the vehicle oriented to the right. Before completing the generalization test participants rated each stimulus in terms of their speed via a six-item scale from "Very slow" to "Very fast", and their direction as either "To the left" or "To the right". The instruction before the generalization test read:

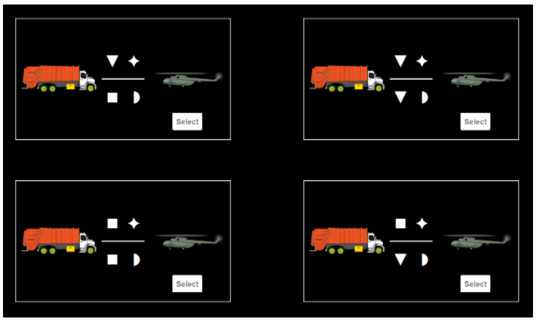
> *In the next phase you will now see pictures of different kinds of vehicles presented together. Similar to previous phases of this task you will see symbols presented between these vehicles. Based on*

your experiences with these symbols in the study so far, your goal is to select the appropriate box. Respond as accurately as you can.

On a given trial in the generalization test a pair of stimuli were presented in four selection boxes similar to those described above for Cfunc training. The four selection boxes differed in the precise constellation of Crels and Cfuncs that appeared between the vehicle stimuli (see Figure 3). Participants were required to select the appropriate box for each pair of stimuli and arrangement of Crels and Cfuncs. The generalization test consisted of 30 trials without response feedback.

Figure 3

A Screenshot of a Trial in the Generalization Test in Phase 5



Results

Only data from the 22 participants exposed to all stages including Cfunc training and testing were subjected to analysis. Percent accuracy scores indicated that responding during Crel testing was above chance level; M = 66.6, SD = 27.6, $t(21) = 2.83$, $p < .01$, 90% CI = [58.9, 100], BF = 4.9. Similarly, percent accuracy scores indicated that responding during Cfunc testing was above chance level; M = 69.2, SD = 27.4, $t(21) = 3.29$, $p < .01$, 90% CI = [61.5, 100], Bayes Factor (BF) = 12. The individual data for the Cfunc test are displayed in Figure 4. Notably, 10 of the 22 participants achieved test accuracies ≥ 83% (i.e., 50 or more accurate responses across the 60 test trials). This 83% benchmark was of interest because it indicates that responding during test was maintained at the same level as the training criterion. Percent accuracy scores from the generalization test were significantly more accurate than chance (i.e., $p = 0.25$); M = 63, SD = 36, $t(20) = 4.87$, $p < .0001$, 90% CI = [52.7, 100], BF = 297. Finally, six of the 21 participants completing all phases of the experiment achieved an accuracy score ≥ 83% on both the car race based Cfunc test and the generalization test. Individual participant accuracies for Crel, Cfunc and generalization tests, and verbal reports from each participant can be found in the supplementary material.

Discussion

With 10 of the 22 participants achieving test accuracies of more than 83% in the car race paradigm, the results of this study provide support for the idea that stimuli can serve a role of selecting the psychologically relevant stimulus functions that are transformed along stimulus relations. Of course, with 12 of the 22 participants failing to respond with high levels of accuracy, the transformations of stimulus functions were not reliably brought under experimenter control for all participants. We cannot conclude that this procedure is very effective in producing Cfuncs. This may be due to how the Cfuncs for speed and direction were established separately. In these training trials the property of the racecars that was not being trained was held constant (e.g., when training speed both race cars went in the same direction). On the selection screen during these phases Crel and Cfunc stimuli specified how the race cars' performances compared with the sample race car's performance along dimensions of speed *and* direction. So, although only one dimension and therefore one Crel and Cfunc pair was relevant to selecting the appropriate race car, two Crel and Cfunc pairs were presented on these screens. The second Crel and Cfunc pair provided information irrelevant to training the Cfunc that was the target of the procedure, yet still varied across trials. This may have impeded establishing Cfuncs. In addition to this the accuracies during Crel testing were modest. This was perhaps due to the procedures for establishing and testing Crel stimuli taking different formats.

Experiment 2

In Experiment 2 some alterations were made to the procedures of Experiment 1. These adjustments are noted in the procedure section and were designed to increase the proportion of participants achieving accuracy of 83% or greater in the car race based Cfunc test.

Method

Participants

46 participants (30 female, mean age = 32 years, *SD* = 11) began the experiment.

Procedure

The procedure established and tested Crel and Cfunc stimuli in a similar manner to Experiment 1 but with some alterations. First, Experiment 2 employed a different format for Crel training and testing format than in Experiment 1. This format has been successful in studies previously conducted in our lab (https://osf.io/w2n9g/). Both the training and testing format presented a Crel stimulus before a screen displaying three circles, a sample circle and two comparison circles, only one of which is the same color as the sample circle. Different colored circles were presented in Crel training and testing. The second adjustment relative to

Experiment 1 was in Phase 3, and specifically related to the training for Cfuncs for direction and speed. In these phases, only the Crel and Cfunc pair relevant to the target stimulus property were presented (see right panel of Figure 2). Thus, in each selection box only one Crel and Cfunc pair appeared between the sample racecar and each racecar, and not two Crel and Cfunc pairs as shown in the left panel of Figure 2. For example, when establishing the Cfunc for direction the Crel and Cfunc pair specifying speed were not presented. In another change, when establishing the Cfunc for speed the sample racecar always moved toward the finish line. This was to avoid presenting trials in which the speed and direction of the winning racecar were different from the sample racecar but only the difference in speed was specified by the Crels and Cfuncs presented on screen. It was thought that due to the salience of the direction dimension, such trials might undermine the effort to establish a Cfunc that specifies speed only. An instruction alerting participants to the change in phase was inserted between training phases for each Cfunc also. This instruction read “Phase complete! You are about to begin the next phase.” Finally, the maximum length of the training phases was reduced from five 30-trial blocks, to three 30-trial blocks. This applied to Crel training, Cfunc for speed, Cfunc for direction, and mixed Cfunc training phases.

Results

Only data from the 23 participants achieving accuracy of ≥ 66% during the Crel test and who completed Cfunc training and testing were subjected to analysis. For these participants, percent accuracy scores indicated that responding during Crel testing was above chance level; M = 95.2, SD = 5.8, $t(22)$ = 37.7, p < .0001, 90% CI = [93.6, 100], BF = BF > 1.5×10^{18}. Similarly, percent accuracy scores indicated that responding during Cfunc testing was above chance level; M = 70.8, SD = 27.7, $t(22)$ = 3.66, p < .001, 90% CI = [63.3, 100], BF = 27. The individual data for the Cfunc test are displayed in Figure 4. Notably, 11 of the 23 participants achieved test accuracies ≥ 83% (i.e., 50/60). This is similar to the 10/22 participants achieving this level of accuracy in Experiment 1. Percent accuracy scores from the generalization test were above chance level (i.e., p = 0.25); M = 57.6, SD = 30.6, $t(21)$ = 5.0, p < .0001, 90% CI = [57.6, 100], BF = 437. Finally, five of the 22 participants completing all phases of the experiment achieved an accuracy score ≥ 83% on both the car race based Cfunc test and the generalization test.

Discussion

With 11 of the 23 participants achieving test accuracies of more than 83%, Experiment 2 failed to increase experimenter control over behavior relative to Experiment 1. That said, Experiment 2 provides further support for the idea that certain stimuli serve a role of selecting the psychologically relevant stimulus functions that are transformed along stimulus relations.

In Experiment 2, when establishing Cfuncs for each stimulus dimension only one Crel and Cfunc pair was presented – the Crel and Cfunc pair specifying the target stimulus dimension. However, due to removing “irrelevant” Crel and Cfunc stimuli, participants in Experiment 2 could complete phases establishing Cfuncs for each stimulus dimension without attending to the programmed Cfuncs for speed and direction. Participants need only identify the important dimension within the phase (i.e., whether racecars within the phase differed in terms of speed or direction), observe the sample racecar, and select a race car based on the Crels for same and different. During mixed Cfunc training participants were required to attend to two pairs of programmed Crels and Cfuncs that specified speed and direction. This is a difficult task if prior to mixed Cfunc training participants have only attended to the Crel stimuli. The difficulty described here may have been encountered by the seven of the 23 participants in Experiment 2 who achieved the training criterion (i.e., ≥ 85% accurate across the previous 20 trials) in the training phase for each Cfunc before failing to meet the training criterion on mixed-trials and the Cfunc test.

When establishing Cfuncs for speed and direction in Experiment 1, two Crel and Cfunc pairs were presented between the sample racecar and each racecar; one Crel and Cfunc pair that specified the target dimension (e.g., speed) and one Crel and Cfunc pair that specified the “irrelevant” stimulus dimension (e.g., direction). Each Cfunc training phase (i.e., Cfunc for speed, Cfunc for direction) was defined by the racecars having the same property along the irrelevant stimulus dimension. That is, when training the Cfunc for speed all racecars in a given trial would go the same direction. This meant that the Crel and Cfunc pair specifying how racecars compared to the sample racecar along the “irrelevant” dimension was identical, and could not be used to select the winning racecar. It did not mean that the sample racecar also had that same property along the irrelevant stimulus dimension. Therefore, within each training phase the sample racecar and racecar stimuli varied across both task-relevant dimensions (i.e., speed and direction), which may have made the task more difficult. A quick inspection of the data supports this interpretation. In 55% of exposures to these phases in Experiment 1 the training criterion was met within 60 trials, whereas this figure was 83% for Experiment 2.

A Cfunc specifies a stimulus function or property, and thus partly involves a relation between a stimulus and variation in a stimulus property (e.g., in the phrases “low speed”, “moderate speed”, and “high speed” the word speed bears a relation to the various speeds of various stimuli). When establishing a Cfunc, the relation between the Cfunc stimulus and the variation in a particular stimulus property should be more obvious when varying stimuli only along the stimulus dimension with which we seek to establish a relation to a Cfunc. That is, it seems likely that the relationship between a stimulus (e.g., the word “speed”) and the stimulus dimension to which it refers (e.g., the speeds of various objects) will be more readily discriminated if the stimulus is presented in the context of stimuli varying only along that stimulus dimension (i.e., they only differ in speed) and not along various other stimulus dimensions also (e.g., differing along multiple dimensions such as speed, size, direction of movement etc.). It seems plausible that a more efficient way to generate Cfuncs is to present a series of situations in which the stimuli differ only along one task-relevant dimension, and to present both relevant and irrelevant Crel and Cfunc pairs in this situation. Across trials in these situations only the relevant Crel and Cfunc pair will change because this pair will covary with changes in the target stimulus property. This should make it easier to discriminate the relationship between the target Cfunc property and the relevant Crel and Cfunc pair.

To apply this analysis to production of Cfuncs for direction and speed in the car race paradigm two sets of trials were designed for Experiment 3. In the set of trials designed to establish a Cfunc for direction all racecars moved slowly, but the direction they moved varied across trials. Thus, changes in only one pair of symbols covaried with these inter-trial changes in direction (i.e., the programmed Crel and Cfunc pair specifying direction indicated either ‘same direction’ or ‘different direction’), and the other pair of symbols did not change throughout these trials (i.e., the programmed Crel and Cfunc pair specifying speed always indicated ‘same speed’ for both racecars). Similarly, in the set of trials designed to establish a Cfunc for speed all racecars moved forward, but did so either quickly or slowly. In these trials, changes in only one pair of symbols covaried with these inter-trial changes speed (i.e., the programmed Crel and Cfunc pair specifying speed indicated either ‘same speed’ or ‘different speed’), and the other pair of symbols did not change throughout these trials (i.e., the programmed Crel and Cfunc pair specifying direction always indicated ‘same direction’). It was suspected that an important source of control here was likely to be discriminating the difference between situations in which one stimulus dimension varies and is task relevant (e.g., speed only) and the situations in which the other stimulus dimension varies and is task relevant (e.g., direction only). To facilitate this discrimination participants could be exposed multiple times to a brief series of each kind of trial (e.g., 30 trials from set 1, followed by 30 trials from set 2 before returning to set 1 etc.). The final stage showed racecars that vary across trials in both speed and direction. This was the approach taken in Experiment 3.

Experiment 3

Method

Participants

38 participants (20 female, mean age = 32 years, *SD* = 9) began the experiment.

Procedure

In Experiment 3, the procedure for establishing and testing Crels and Cfuncs differed from Experiment 2 in four respects. First, Experiment 3 terminated early for participants failing to achieve accuracy ≥ 66% in Crel testing. The second adjustment was to the Cfunc training procedure. Racecar stimuli in each Cfunc training phase varied along one stimulus property dimension only (i.e., only slow cars when establishing the Cfunc for direction, and only forward moving cars when establishing the Cfunc for speed). Third, both Crel and Cfunc pairs were presented at all stages as shown in the left panel of Figure 2. Fourth, training blocks for each Cfunc were intermixed and terminated either after 6 blocks of training or when the training criterion was met for both kinds of block.

Results

Only data from the 20 participants who achieved accuracy of ≥ 66% during the Crel test and who completed Cfunc training and testing were subjected to analysis. Percent accuracy scores during Crel testing were above chance level; $M = 93.7$, $SD = 8.2$, $t(19) = 23.9$, $p < .0001$, 90% CI = [91.3, 100], BF > 3.9×10^{12}. However, percent accuracy scores indicated that responding during Cfunc testing was not above 50% at a group level; $M = 50.4$, $SD = 19$, $t(19) = 0.09$, $p = .46$, 90% CI = [44.8, 100], BF = 0.2. The individual data for the Cfunc test are displayed in Figure 4. Notably, only two of the 20 participants achieved test accuracies ≥ 83% (i.e., 50/60). This was much lower than the roughly 50% of participants achieving this level of accuracy in Experiments 1 and 2. Percent accuracy scores from the generalization test were above chance level (i.e., $p = 0.25$); $M = 38.2$, $SD = 20.7$, $t(18) = 2.78$, $p < .01$, 90% CI = [31.9, 100], BF = 4.4. Finally, none of the 19 participants completing all phases of the experiment achieved an accuracy score ≥ 83% on both the car race based Cfunc test and the generalization test.

Discussion

With two of the 20 participants achieving test accuracies of more than 83%, Experiment 3 dramatically failed to increase experimenter control over behavior relative to Experiment 2 (see Figure 4). The training provided in Experiment 3 produced effective Cfuncs for fewer participants than the training in Experiments 1 and 2. This relative failure is not likely to be explained by ineffective Crel control, which was quite well established as evidenced by the high average accuracy scores on the Crel test. The failure is rooted in the kind of Cfunc training provided in Experiment 3. When establishing the Cfunc for direction in Experiments 1 and 2, the relationships between the racecars' properties and the sample racecar's properties differed only in terms of direction. This meant that both racecars went the same speed, even if that speed was different than the sample racecar, but one racecar went in the same direction as the sample racecar and the other racecar went in the opposite direction to the sample racecar. When training the Cfunc for speed, both racecars went the same direction, but one racecar went the same speed as the sample racecar and the other racecar went a different speed as the sample racecar. Effectively, when training a given Cfunc these procedures selectively varied the relationships between the stimuli with regard to that stimulus property. In these experiments, roughly 50% of participants had response accuracies ≥ 83% at test.

Cfunc training in Experiment 3 took a different tack. The properties of the stimuli were selectively varied, and by extension so were the relationships between the stimuli with regard to their properties. For example, when establishing the Cfunc for direction in Experiment 3 all racecars, including the sample racecar, went the same speed. Similarly, when establishing the Cfunc for speed all racecars went the same direction. In Experiment 3 the design of Cfunc training contexts focused on the relation between Cfuncs and stimulus properties by varying only one stimulus property across training trials designed to establish each Cfunc. However, holding one stimulus property constant within and across trials obviated the need for selection among properties in the training context. In hindsight, given that the training context did not require it, it is unsurprising that selective action of Cfuncs was not reliably observed at test.

Experiment 4

In the initial training phases of Experiment 3 the properties of the racecars varied along one stimulus dimension only (i.e., speed or direction). Such training was highly ineffective and was abandoned. The Cfunc training in Experiment 4 reverted to the kind found to be somewhat effective in Experiments 1 and 2 – varying the racecars' properties of speed and direction throughout the car race paradigm, and selectively varying the relationships between stimuli with regard to these properties. For example, two racecars might be related to the sample racecar in the same manner with respect to speed (e.g., both same speed or both different speed), but be related to the sample racecar in a different manner with respect to direction (e.g., same direction vs different direction). Unlike in Experiment 3, the properties of the racecars were not held constant in any subset of trials, and experimental control was exerted at the level of the relationship between the stimuli with regard to their properties as in Experiments 1 and 2. To increase the number of participants producing high test accuracy scores in Experiment 4, elements of the training provided in Experiments 1 and 2 were combined. Specifically, participants were exposed to the initial training phase from Experiment 2 followed by the initial training phase from Experiment 1. The initial training phases in Experiment 2, which presented only the Crel and Cfunc pair relevant to the Cfunc being established (see right panel of Figure 2), were successfully completed by 74% of participants (see Table 2), compared to 54% in Experiment 1, which presented two Crel and Cfunc pairs. However, 83% of participants that successfully completed the training in Experiment 1 passed the Cfunc test. This figure was only 64% in Experiment 2. The intended effect of exposure to one kind of training followed by the other was increased success in the Cfunc test relative to the previous experiments. Subsequent to completing these initial training phases, participants were exposed to mixed training trials and Cfunc testing as per the procedures from the three previous experiments. Finally, Experiment 4 included a Cfunc absent test of Cfunc control which was added to the car race paradigm after the regular test of Cfunc control, to assess whether the programmed Cfunc was indeed controlling participants responses (see below).

Method

Participants

35 participants (21 female, mean age = 36 years, *SD* = 12) began the experiment.

Procedure

The procedure for Experiment 4 combined elements from the previous experiments. Crel training and testing took precisely the same format as in Experiment 3, including early termination of the experiment for participants not achieving accuracy ≥ 66% in Crel testing. As in Experiments 1 and 2, stimuli in each Cfunc training phase varied along both stimulus property dimensions, and the relationships between the stimuli with regard to their properties were selectively varied across trials. In contrast to the previous experiments, each Cfunc was trained in two separate stages before mixed training trials. In the first stage only the Crel and Cfunc pair relevant to the Cfunc being trained were presented as depicted in the right panel of Figure 2. In the second stage both Crel and Cfunc pairs were presented as shown in the left panel of Figure 2. In these stages the Crel and Cfunc pairs for speed and direction occurred in the same location in the selection box. In the mixed trials phase, the locations of the Crel and Cfunc pairs for speed and direction were counterbalanced across top and bottom locations as in all previous experiments. Due to the extended Cfunc training, the maximum number of

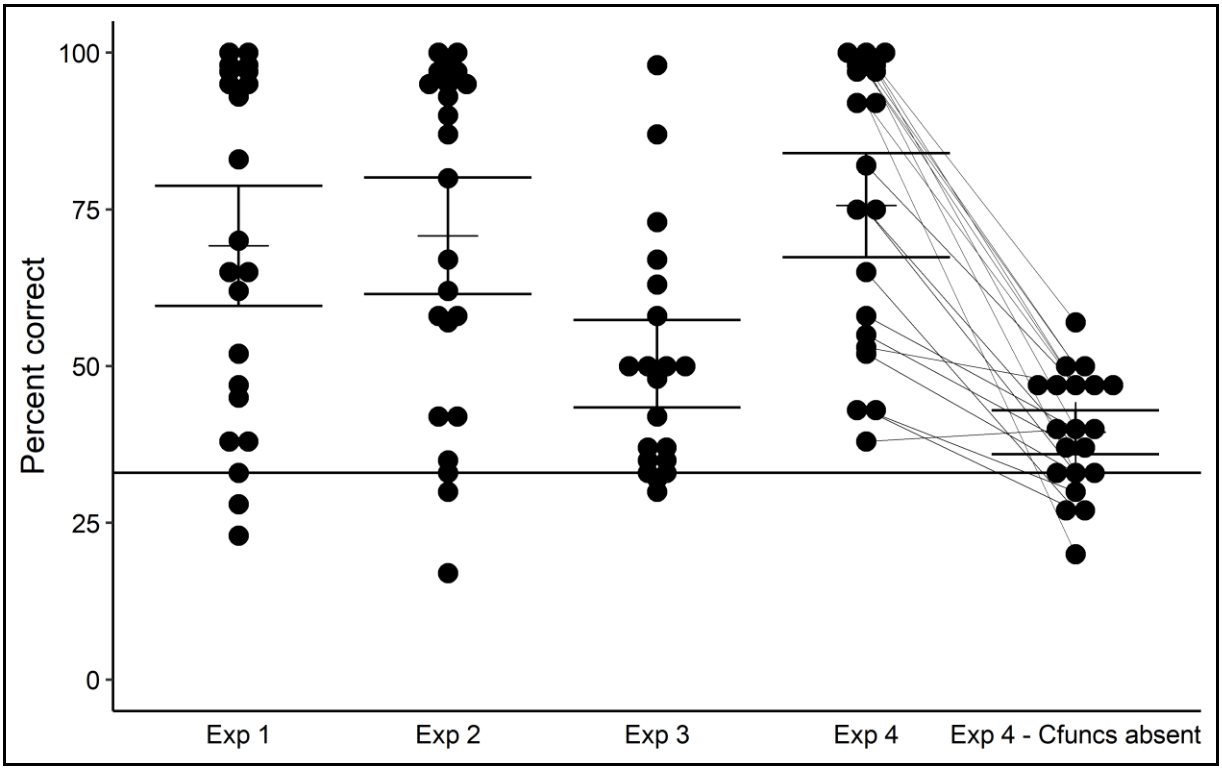
Cfunc training blocks was increased relative to experiments 2, and 3 from 9 to 15 blocks, which is the same number of blocks as in Experiment 1. Following the Cfunc test participants were exposed to a Cfunc absent test. The Cfunc absent test consisted of 30 trials that took the same general format as the Cfunc test, but programmed Cfunc symbols were not presented to participants in the selection boxes during the selection screen. Only programmed Crel symbols were presented between the racecars in the selection boxes. The purpose of including a Cfunc absent test was to facilitate comparison of behavior in conditions when the programmed Cfuncs were present and absent, thereby allowing an assessment of the stimulus control exerted by the programmed Cfuncs. Note that the Cfunc absent test presented a subset of the regular Cfunc test trials. This was because in some regular trials the sample racecar goes slowly in the wrong direction and in other trials the sample racecar goes quickly in the right direction. In these trials the performance of the winning racecar is identical to or opposite to that of the sample racecar in terms of both speed and direction. Trials of this kind were not presented, because in these trials the winning racecar could be selected if there were two Crels for same, or two Crels for different. This would mean that the winner could be selected even without programmed Cfuncs, which could artificially inflate accuracies.

Results

Only data from the 20 participants who achieved accuracy of ≥ 66% during the Crel test and who completed Cfunc training and testing were subjected to analysis. Percent accuracy scores during Crel testing were above chance level; $M = 96.5$, $SD = 3.3$, $t(19) = 62.5$, $p < .0001$, 90% CI = [95.5, 100], BF > 9.5×10^{19}. Percent accuracy scores indicated that responding during Cfunc testing was significantly above 50% at a group level; $M = 75.7$, $SD = 22.6$, $t(19) = 5.07$, $p < .0001$, 90% CI = [68.9, 100], BF = 390. The individual data for the Cfunc test are displayed in Figure 4. Nine of the 20 participants achieved test accuracies ≥ 83% (i.e., 50/60). This is similar to the roughly 50% of participants achieving this level of accuracy in Experiments 1 and 2. The maximum accuracy score achieved by a participant on the Cfunc absent test was 57% ($M = 39.3$, $SD = 9.5$). Percent accuracy scores from the generalization test were above chance level (i.e., $p = 0.25$); $M = 62.1$, $SD = 33.4$, $t(19) = 4.97$, $p < .0001$, 90% CI = [52.2, 100], BF = 324. Finally, eight of the 20 participants completing all phases of the experiment achieved an accuracy score ≥ 83% on both the car race based Cfunc test and the generalization test.

Figure 4

Individual Data from the Car Race Based Cfunc Tests



Note. The percent accuracy score for each participant in the car race Cfunc test in Experiments 1, 2, 3, 4 and the Cfunc absent test in Experiment 4. The bars indicate the group mean and its associated 90% confidence interval. Differences in individual scores on the two tests in Experiment 4 are traced by grey lines. Chance level is indicated by a horizontal line at 33.

Table 2

Summary statistics for Car Race Based Cfunc Training and Testing in the Four Experiments.

	Cfunc direction		Cfunc speed		Cfunc mixed		Cfunc test	
	#Passing	# trials	#Passing	# trials	#Passing	# trials	≥ 83%	accuracy
Exp. 1	17/22	64 (50)	12/22	97 (55)	12/22	99 (57)	10/22	69 (27)
Exp. 2	21/23	34 (22)	17/23	39 (21)	12/23	53 (36)	11/23	71 (27)
Exp. 3	16/20	43 (28)	17/20	41 (29)	2/20	87 (9)	2/20	50 (19)
Exp. 4	19/20	27 (19)	15/20	39 (32)	14/20	45 (34)	9/20	76 (23)

Note. The summary statistics are the number of participants achieving training criteria and mean number of trials completed in the car race paradigm in each experiment. Standard deviations are provided in brackets where applicable. Experiment 4 data for each Cfunc refers to the second training component.

Discussion

Experiment 4 provides positive results supporting the idea that particular stimuli select which functional properties transform in accordance with derived stimulus relations. The first result supporting this idea is the nine individuals completing the car race based Cfunc test with accuracies ≥ 83%. The second result is the reduction in accuracy observed when the programmed Cfuncs were not presented in the Cfunc absent test (see Figure 4). The number of participants achieving high test accuracies in Experiment 4 (i.e., 9/20) was no greater than observed in Experiments 1 and 2. This is somewhat surprising given that a greater number of participants met training criteria in each phase of Experiment 4 (i.e., 14/20) than in previous experiments. Of the five participants successfully completing training but not achieving high accuracies at test, three achieved accuracies ≥ 75% at test. The other two of these five participants achieved training criteria within 19 trials, which terminated training trials with three racecars (i.e., the training phase most similar to the test phase). It is speculation on our part, but these participants may not have received enough of this kind of training. In general, the results from Experiment 4 were more convincing than those from previous experiments.

General discussion

Four experiments investigated the selective transformation of derived stimulus function, and how Cfunc stimuli (i.e., stimuli that select which functions are transformed) may be established. The experiments employed a car race paradigm with two components: i) a sample racecar screen which showed the performance of a sample racecar, and used experimentally-engineered symbols to specify how the performance of other racecars was related to that of the sample racecar, and ii) a car race screen showing the other racecars race. In each experiment two symbols were established as cues for the relations of same and different, and two symbols were established as cues for the stimulus features speed and direction. The experiments differed in the kind of training they provided. In Experiment 1 the Cfuncs for speed and direction were established in separate phases in which only the Crel and Cfunc pair being established in each phase differed within trials. Experiment 2 also provided separate training for each kind of Cfunc, however when establishing a Cfuncs for speed or direction, only the Crel and Cfunc pair the experimenter designated as specifying the given property (i.e., speed or direction) were presented to participants. The pattern of results in these experiments was highly similar with approximately 50% of participants achieving high levels of accuracy in both experiments, showing that stimuli can function as Cfunc, be it only in a subset of the participants. Experiment 3 involved separate Cfunc training phases in which the racecar stimuli differed along the target dimension only. This meant that when establishing a

Cfunc for speed, for example, the racecar stimuli all went the same direction. The results from Experiment 3 indicated that training which varied only the stimulus property related to the Cfunc was an ineffective method for establishing selective action. Experiment 4 combined the training provided in Experiments 1 and 2, and included a test of Cfunc control involving the removal of programmed Cfuncs. The results of Experiment 4 indicated that Cfuncs which selected functional properties to be transformed via stimulus relations had been generated for at least a subset of participants.

This study provides a demonstration of a key component of arbitrarily applicable relational responding - the selective action of Cfunc control over derived transformations of functions (Hayes & Hayes, 1989). Some readers might take issue with the nature of the transformations of functions described here. Strictly speaking the experiment requires the transformation of stimulus properties, and not of functions such as discriminative, reinforcing, or motivational functions. Nonetheless, the transformation of the functional properties of stimuli as achieved here is sufficient to demonstrate the selective action of Cfunc control. Indeed, Hayes and Hayes (1989, p. 170) describe Cfuncs as "… the contextual stimuli that select particular psychologically relevant, nonrelational stimulus functions that transfer in a given situation …" They go on to describe the perceptual functions of taste, texture, and sight, and give an example involving the taste function of a lemon. The stimulus properties of speed and direction transformed by relational responses in the current study fit this early definition of the kind of properties specified by Cfunc stimuli (see also Hayes et al., 2001, pp. 32-33).

The kind of Cfunc control described here differs from that described by Stewart et al. (2013) insofar as it involves transformations of stimulus functions, rather than joint control of Crel and Cfunc stimuli over the selection of appropriate comparison stimuli in a complex MTS procedure. We can conclude the functions of racecar stimuli were transformed in our procedure based on the proportion of winning racecars that were selected. This Cfunc control exemplified in this study is also different to that described by, for example, Perez et al. (2021), because it involves the selective transfer of stimulus functions, and not contextual control of stimulus functions at test. The demonstration provided here is in keeping with Hayes and Hayes (1989) original definition of Cfunc control. However, these studies highlight the different senses in which the term Cfunc has been used in the literature to date; a stimulus specifying a particular functional property (e.g., Stewart et al., 2013), a stimulus exerting the control over stimulus functions (e.g., Perez et al., 2021), and a stimulus exerting control over the transformation of stimulus functions as described here.

The procedures described here provide examples of a method that can produce Cfuncs that select among the functional properties of particular stimuli, albeit with a limited rate of success. Attrition rates were high and yield of successful completion was lower than 50% for all studies. This could be partly attributable to online data collection, and partly attributable to participants failing to achieve test accuracy during Crel training. It is mainly attributable to the long and difficult Cfunc training procedure. During training the task requires discriminating the position of the finish line, discriminating the functional properties of the sample racecar, discriminating differences in the functional properties of the racecars, and discriminating that particular programmed Crels and Cfuncs covary with the relationship between the performances of the sample racecar and the racecars. In everyday language terms, during testing participants must transform the properties of multiple stimuli in accordance with Crels and Cfuncs, compare the performances that could be predicted on the basis of the Crels and Cfuncs, before making their selection. This is not easily done. However, as argued in the introduction, demonstrating the selective action of Cfuncs requires a complex environment with multiple stimuli, multiple functions and multiple relations between them. Introducing these components slowly as done in Experiment 4 was somewhat effective, but came at the cost of a longer procedure. The task could be simplified somewhat. One method to increase yield might involve adopting a stricter training criterion, or providing more substantial incentives. Another option is to use other types of stimuli as Crels and Cfuncs, such as textual stimuli. Another way to increase yield may be to engineer a compound Crel and Cfunc function for a single stimulus instead of combinations of two kinds of Crel and Cfunc. Although this option would preclude any test of Cfunc control involving the removal of programmed Cfuncs, participants would not need to learn how to combine the Crel and Cfunc stimuli.

Establishing repertoires of arbitrarily applicable relational responding has been a recent focus within applied behavior analysis (Dixon, 2014). Other researchers have focused on increasing the strength and complexity of these repertoires (Cassidy et al., 2011). Another aspect of establishing a repertoire is appropriate contextual control of the kind described here. Much of the value of the current work depends on whether it is useful to those establishing and refining patterns of relational responding in applied contexts. In this regard, it may be useful to create a table-top procedure based on the paradigm described here which uses physical objects of different speeds and directions. Such a procedure could return this work to the context that inspired it (i.e., Belisle et al., 2020). In any case, investigating how Cfuncs may be efficiently established is likely to be informative for those engaged in basic and applied work on arbitrarily applicable relational responding.

Finally, another area of research to which the current work is related is the feature transformation framework (De Houwer et al., 2019). The framework deals with the various ways stimulus features transform between source and target stimuli, which may or may not be part of the same stimulus object. Halo effects, which involve changes in one stimulus feature due to information about another stimulus feature (e.g., attractive people are often rated as more intelligent than unattractive people; Landy & Sigall, 1974) and evaluative conditioning effects, which involve changes in evaluative functions, are two examples of the kinds of effects dealt with by the framework. These kinds of effects typically imply that a single transformation has occurred. The current study shows that multiple stimulus features may be transformed in at least two ways, a kind of feature transformation that is more complex than typically reported (e.g., evaluative conditioning; Hofmann et al., 2010). Furthermore, contextual control over feature transformations such as that reported here is not a frequent focus of research on halo effects and evaluative conditioning. As such, the current study describes feature transformation effects that may be of interest to researchers working on halo effects and in evaluative conditioning research, regardless of their research tradition.

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Supplementary Table 1.
Accuracy scores for the Crel, Cfunc and generalization tests, maximum Cfunc training accuracy, and verbal reports for the individual participants completing Experiment 1.

Participant	Crel Test	Cfunc Train	Cfunc Test	■	▼	◗	✦	Gen. Test
18345	100	85	100	Different/ opposite	Same	Speed	Direction	27
83c0f	97	85	100	same	different	direction	speed	17
e8570	97	85	98	Different	Same	Speed	Direction	97
1a374	50	85	98	different	direction	speed		90
679ba	93	85	97	same	different	direction	speed	97
86bed	63	85	97	Different/ Opposite	Same	Speed	Direction	100
92d00	70	85	95	Opposite	Same	Speed	Direction	23
d823b	40	85	95	change	stay the same	speed	direction	93
1ce82	47	85	93	same	different	change	no change	100
e0d6c	67	85	83	opposite	same	speed	direction	37
dce05	93	70	70	Same	Opposite/ Different	Fast	Slow	100
b4fc1	93	85	65	Same	Direction	Speed		83
8e6e1	27	75	65	NA	NA	NA	NA	NA
319a0	40	85	62	SAME	DIFFERENT	SAME	DIFFERENT	13
1bfe8	97	80	52	Change State	Stay The same	Change State		93
5628c	63	40	47	Medium Square	Down-Pointing Triang	Right Half Circle	Four Pointed Star	97
9f18f	93	60	45	Go right	Go fast	Go slow		20
1c159	47	60	38	Triangle	Half Circle	Diamond		17
4588a	3	65	38	forward	backward	right direction	wrong direction	30
83e33	90	65	33	Forward	Fast	Slow		80
9f274	47	60	28	forward	reverse	slow	speed	77
e7d00	50	50	23	REVERSED	WEAK	BOOST		100

Supplementary Table 2.
Accuracy scores for the Crel, Cfunc and generalization tests, maximum Cfunc training accuracy, and verbal reports for the individual participants completing Experiment 2.

Participant	Crel Test	Cfunc Train	Cfunc Test	■	▼	◗	✦	Gen. Test
ca30d	97	85	100	Opposite	Same	Speed	Direction	27
ce7a1	97	85	100	Opposite	Same	Speed	Direction	97
718bb	43	85	98	opposite	equal	Marker for speed	Marker for direction	33
ca7d2	100	85	97	Opposite	Same	Direction	Speed	90
e51c5	100	85	97	Opposite	Same	Speed	Direction	27
25631	97	85	95	opposite/ untrue	correct/ true	speed	direction	23
6519c	97	85	95	Opposite	Same	Speed	Direction	100
2f6be	50	85	95	Same	Opposite	Speed	direction	83
d3315	87	85	93	different/ opposite	same	speed	direction	77
94e64	100	85	90	change	maintain	speed	direction	97
ae780	63	85	87	Same	Opposite	Direction	Speed	77
e28d1	53	80	80	same direction	opposite direction	direction	speed	40
27c6c	87	55	67	unchange	change	direction	speed	77
8ad57	100	70	62	opposite direction	same direction	I don't know	Speed maybe?!	83
5059c	100	85	58	One direction	Opposite	One direction	Opposite	30
9dc3b	93	75	58	Opposite speed	Copy speed	Same direction	Inverse direction	100
432b3	50	70	57	Goes same way	Goes half speed	Goes fast		17
e2031	87	55	42	copy car	no idea	no idea	no idea	27
f3cfd	50	70	42	less speed	over the line	the finish line		27
33cac	83	65	35	same direction	opposite direction	slower	power	20
35f1b	50	55	33	NA	NA	NA	NA	NA
56156	83	70	30	Opposite of sample	Same as sample	Speed	Direction	47
72fec	47	50	17	I have no clue	I have no clue	I have no clue	I have no clue	63

Supplementary Table 3.
Accuracy scores for the Crel, Cfunc and generalization tests, maximum Cfunc training accuracy, and verbal reports for the individual participants completing Experiment 3.

Participant	Crel Test	Cfunc Train	Cfunc Test	■	▼	◗	✦	Gen. Test
b3e18	93	80	98	same	opposite	same when on top	flip when on top	23
3498b	53	85	87	same	unsure	same	opposite	23
e50ac	93	80	73	opposite	same	slow	quick	27
ee234	100	80	67	same	different	direction	speed	60
a8c14	100	65	63	NA	NA	NA	NA	NA
0a115	100	75	58	the same	opposite	unsure	unsure	40
3203	100	65	50	the same	the opposite	forwards	backwards	73
8dc6b	100	70	50	Identical	Run	Slow		20
a53eb	97	85	50	same	different	speed	direction	30
9efc1	63	75	50	move backwards	override if above	if above ignore		23
37aa9	97	55	48	against	fast	slow		40
6e2c3	87	65	42	correct direction	speed increases	not sure	not sure	37
96045	93	40	37	backwards	direction	speed		27
553bc	90	50	37	fast speed	slow speed	back fast	back slow	43
f13c6	97	60	35	back	fast	left	right	33
6d468	87	75	35	Opposite direction	Same direction	Opposite direction	Same direction	10
c1f58	83	55	33	Go	Unsure	Move		37
fef9e	67	30	33	Forward	Backward	Slow	fast	37
864d9	93	50	32	forward	back	slow	fast	43
ff9d9	100	55	30	Probable win	Dont know	Dont know	Not sure	73

Supplementary Table 4.
Accuracy scores for the Crel, Cfunc and generalization tests, maximum Cfunc training accuracy, and verbal reports for the individual participants completing Experiment 4.

Participant	Crel Test	Cfunc Train	Cfunc Test	■	▼	◗	✦	Gen. Test
908c6	100	85	100	opposite direction	same direction	same speed	opposite speed	43
6268f	93	85	100	Same	opposite	car direction	speed	97
6c9be	93	85	100	different	same	speed	direction	100
d13ba	100	85	98	Same action	Opposite action	Direction of action	Speed of action	100
42f58	97	85	98	same as sample car	opposite to sample	direction	speed	100
8f2c2	97	85	97	different	finish line	speed		93
ca0e3	93	85	97	The same	The opposite	Direction	Speed	90
2bdd4	93	85	92	opossite	same	speed	direction	97
c66e1	90	85	92	Same	Different	Direction	Speed	100
4bdf4	100	85	82	correct way	opposite way	Side of the track	Speed	27
ade28	100	85	75	Same	Speed	Direction		86
b2c14	100	85	75	wrong	right	speed	direction	27
2b058	100	65	65	correct	wrong	no idea	speed	30
d4241	97	65	58	Different/rever se	Speed?	direction?		43
c0d2c	100	55	55	opposite	slow	fast		40
3b06c	97	85	53	wrong	correct	speed	direction	70
c6f83	90	85	52	opposite direction	same direction	slow speed	same direction	20
0c84f	97	60	43	Opposite direction	Same direction	not sure	not sure	33
7e5b2	97	55	43	Opposite	Same direction	Unsure	Unsure	13
67271	97	45	38	fast	slow	back		33