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研究課題名（和文）ヒトの認知の基盤となる神経計算学的圏論

研究課題名（英文）A category theory approach to human cognition

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研究成果の概要（和文）：認知におけるシステム性とは、課題の普遍的構造に基づいた表象の学習と定義される。本研究は、圏論に基づいてヒトの認知のシステム性を理解することを目的とした。実験では、「システム性の獲得は普遍的構造の学習にかかるコストに依存する」というコスト-ベネフィット仮説を検証した。実験参加者は，学習すべき刺激の要素数を増加（上昇群）または減少（下降群）させながら、普遍的構造が存在する手がかり‐標的連合学習課題を行った。その結果、下降群では全ての要素数条件で普遍的構造が取得されたが，上昇群では要素数の大きい条件でのみ普遍的構造が取得された。本研究により，コスト-ベネフィット仮説の妥当性が支持された。

研究成果の概要（英文）：We explained systematicity in terms of the category theory concept of universal constructions. Experimentally, we tested a theoretical implication that failure of systematicity derives from a cost/benefit trade-off for the universal construction. Participants learned two series of cue-target pair maps whose underlying structures were either products (universal construction), or non-products (control). Each series was learned in either ascending or descending order of size: number of unique cue/target elements constituting pairs. Only performance on the product series was affected by order: systematicity was obtained universally in the descend group, but only on large sets in the ascend group. Consistent with the theory, the results suggest that learning small maps directly, without reference to the underlying product, may be perceived as more cost-effective, i.e., acquisition of a universal construction, hence systematicity, depends on an empirical cost-benefit trade-off.

研究分野：認知科学

キーワード：圏論　普遍的構造　システム性　学習　刺激-反応

１．研究開始当初の背景

Systematicity is a cognitive property whereby the capacity for certain cognitive abilities implies the capacity for certain other (structurally related) cognitive abilities. Yet, this property is not always present. The challenge is to explain both presence and absence of systematicity. Theoretically, we explained systematicity in terms of the category theory concept of universal constructions (Phillips & Wilson, 2016) which applied to learning (Phillips & Wilson, 2016b), language-like capacity in bird calls (Phillips & Wilson, 2016c), and visual attention (Phillips & Takeda, in press).

２．研究の目的

The aim is to test an empirical implication of our theory. The theory says that failure of systematicity derives from a cost/benefit trade-off associated with using a universal construction to complete a cognitive task: participants will demonstrate systematicity when the cost of completing the task via a universal construction is less than the cost of completing the task without a universal construction, otherwise participants will not demonstrate systematicity. The aim is to test this prediction experimentally.

The background theory is briefly described to provide the justification the experiment and hypothesis. In category theory, a product is a universal construction that consists of an (abstract) object and two relations (called morphisms) that extract the component objects. So, for the category whose objects are sets and morphisms are functions, a product in this category is the Cartesian product of two sets, written A x B, that consists of all pairwise combinations (a, b), where a is an element of A and b is an element of B, and two functions that return the first and second component of each pair: (a, b) → a, and (a, b) → b. A product function is a product of two functions f : A → A' and g : B → B', written f x g : A x B → A' x B'. An important property of all products is that they decompose into the components, as shown in Diagram 1. In the context of sets and functions this decomposition implies a trade-off, shown in Diagram 2, as follows. Suppose that sets A and B consists of n elements each. Then the product function f x g is a single mapping of n x n elements (right vertical arrow), whereas the components are two maps of n elements each (totalling 2n elements (left vertical arrow). Thus, there is a trade-off between number of maps (one versus two) and number of elements (n x n versus 2n).

$$
\begin{array}{ccc}
(A,B) & \xleftarrow{\ \phi\ } & A \times B \\
{\scriptstyle (f,g)}\downarrow & & \downarrow{\scriptstyle f\times g} \\
(A',B') & \xrightarrow[\ \psi\ ]{} & A' \times B'
\end{array}
$$

Diagram 1

$$
\begin{array}{ccc}
(a,b) & \xleftarrow{\ \phi\ } & \langle a,b\rangle \\
{\scriptstyle (f,g)}\downarrow & & \downarrow{\scriptstyle f\times g} \\
(f(a),g(b)) & \xrightarrow[\ \psi\ ]{} & \langle f(a),g(b)\rangle\,.
\end{array}
$$

Diagram 2

This trade-off is seen as the basis for whether or not participants demonstrate systematicity in the form of generalization from a subset of training examples to a subset of testing examples. If participants treat pairs of items as a single stimuli, then we expect no generalization to novel test items, because each stimulus is regarded as unique (right side map). However, if participants regards the items as pairs of stimuli, then we expect generatlization to novel test items, because one only requires 2n training examples to correctly predict all remaining test examples.

３．研究の方法

Participants learned two series of cue-target (character-shape) pair maps whose underlying structures were either products (universal construction), or non-products (control). Each series was learned in either ascending or descending order of size: number of unique cue/target elements constituting pairs, which varied from three to six (Figure 1). Example stimuli are shown in Figure 2, and an example learning trial is shown in Figure 3.

As shown in Figure 1, in the product condition there are two ways to compute the mapping: (1) directly as an association from a pair of characters to a coloured shapce, e.g., KP → blue triangle, or (2) indirectly via the constituent mappings, i.e. K → triangle, and P → blue. The hypothesis is that participants will choose the mapping based on their relative

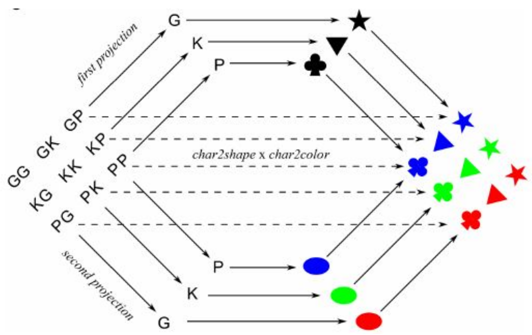

Figure 1

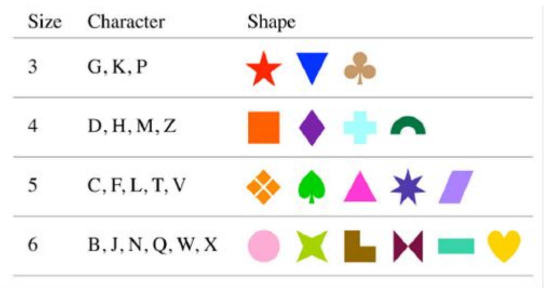

Figure 2

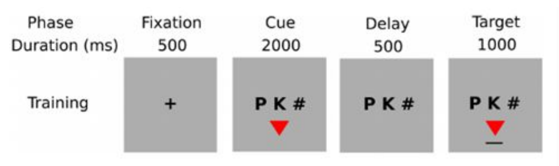

Figure 3

costs. For instance, in the set size 3 condition there are 3 x 3 = 9 possible letter to shape mappings. Half of these mappings are used for training and half are used to assess whether or not the participant induced the underlying product rule. So eventhough there is sufficient information to induce a rule, participants choose the direct route
("shortest distance") to response because there are only a small number of such mappings to be learned, in which case there fail to make the correct responses on the test trials. In the set size 6 condition there are 6 x 6 = 36 possible mappings. Again half of the mappings are used for training and half are used for testing. In this condition, participants choose the indirect mapping, because although each individual mapping involves greater distance there are fewer of them. Compare having to learn the 6 letter to shape mappings plus the 6 letter to colour mappings (totalling 12 mappings) with the 18 direct pair to coloured shape mappings.

4．研究成果

The results from the learning trials showed that both ascending and descending groups learned both the product and non-product tasks (Figure 4). The results from the testing trials showed that only performance on the product series was affected by order: systematicity was obtained universally in the descend group, but only on large sets in the ascend group (Figure 5). Consistent with our theory, the results suggest that learning small maps directly, without reference to the underlying product, may be perceived as more cost-effective, i.e., acquisition of a universal construction, hence systematicity, depends on an empirical cost-benefit trade-off (Phillips, Takeda, & Sugimoto, 2016, 2017).

To further examine the relationship between learning and cost/benefit, we analyzed the data based on participants awareness of the underlying rule. After completing the

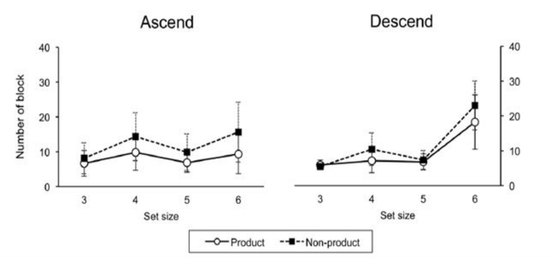

Figure 4

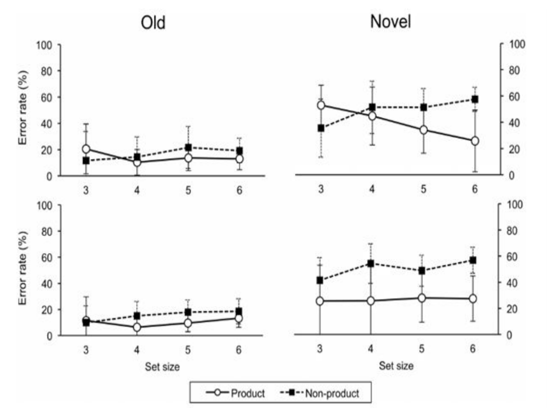

Figure 5

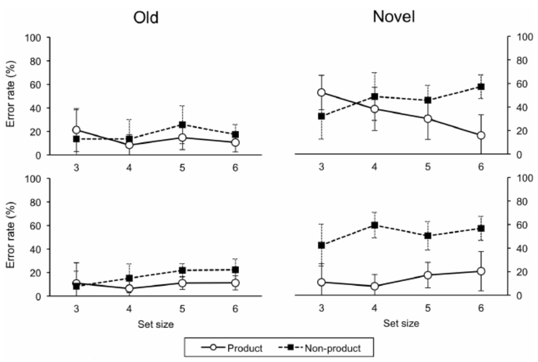

Figure 6

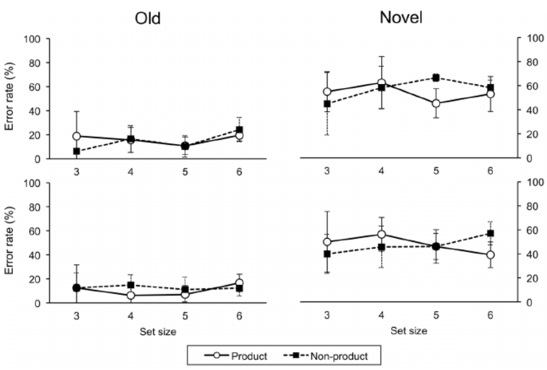

Figure 7

experiment each participant was asked to self-report how they performed the mapping task. Of the 31 participants, 21 reported awareness of the product rule (aware group), 10 reported no awareness (unaware group). The analysis was repeated for each group separately. The results for the aware group mirrored the previous analysis for all 31 participants (Figure 6), whereas there was no significant difference in performance between product and nonproduct conditions for the unaware group (Figure 7). These results further support the importance of perceived cost/benefit tradeoff, although the data do not allow us to determine the cause of awareness.

５．主な発表論文等

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