

## Functional neuroanatomical correlates of contingency judgement

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### ABSTRACT

Contingency judgement is an ability to detect relationships between events and is crucial in the allocation of attentional resources for reasoning, categorization, and decision making to control behaviour in our environment. Research has suggested that the allocation of attention is sensitive to the frequency of contingency information whether it constitutes a negative, zero or positive relationship. The aim of the present study was to explore the functional neuroanatomical correlates of contingency judgement with different frequencies and whether these are distinct from each other or whether they rely on a common mechanism. Using three contingency tasks within a streaming paradigm (one each for negative, zero, and positive contingency frequencies), we assessed brain activity by means of functional magnetic resonance imaging (fMRI) in 20 participants. Contingency frequency was manipulated between blocks which allowed us to determine the neural correlates of each of the three contingency tasks as well as the common areas of activation. The conjunction of task activation showed activity in left parietal cortices (BA 23, 40) and superior temporal gyrus (BA42). Further, the interaction analysis revealed distinct areas that mainly involve lateral (BA 45) and medial (BA 9) prefrontal cortices in the judgment of negative contingencies compared with positive and zero contingencies. We interpret the finding as evidence that the shared regions may be involved in coding, integration, and updating of associative relations and distinct regions may be involved in the investment of attentional resources to varied degrees in the computation of contingencies to make a judgment.

### 1. Introduction

Contingency learning refers to the ability of detecting relations between a cue and a subsequent outcome [1]. It is an important component of our daily life as it facilitates making judgments and controlling events in the environment [1]. Attention is a crucial process for contingency learning – it requires sustained attention to determine the relation between cue and outcome across various possibilities of cue-outcome pairings (see a-d below) [2]. Behavioural research has suggested that contingency judgements have different attentional demands that depend on the frequency of cue-outcome pairs whether they constitute negative, zero or positive contingency frequency [3–4]. Current research

questions whether judgement of contingencies with different frequencies are distinct from each other or whether they rely on common mechanisms.

A typical contingency learning task requires an individual to make a judgment by predicting the relationship between a cue and an outcome when presented many times in separate trials. In each trial, one of four possible pairings may occur:

- Cue is presented (C) and outcome is presented (O)
- Cue is not presented (-C), outcome is presented (O)
- Cue is presented (C), outcome is not presented (-O)
- Cue and outcome are not presented (-C) (-O)

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The relationship between cue and outcome can be modulated by adjusting the frequencies of the cue-outcome pairs accordingly. For instance, the relationship increases toward positivity as the frequencies of (a) and (d) increase (positive contingency), which implies that the frequencies of (b) and (c) decrease. Positive contingency means that the presence or absence of the cue is indicative of the presence or absence of the outcome, respectively. If the frequency of (b) and (c) increases (negative contingency; implying that the frequencies of (a) and (d) decrease), the relation increases toward negativity. Such negative contingency means that the presence of the cue predicts the absence of the outcome and vice versa. If all four cases (a)–(d) have the same frequency, no relation between cue and outcome exists (zero contingency). The contingency between cue and outcome ranges from +1.0 (perfect positive contingency) to –1.0 (perfect negative contingency) and it is symbolized by  $\Delta P$  which is calculated by the difference between two probabilities  $\Delta P = \frac{a}{a+b} - \frac{c}{c+d}$  [1,5].

Research suggests that contingency judgements involve the goal-directed system which is linked with attention, and that the allocation of attention is different for negative contingencies compared to other contingencies [6–8]. For instance, discriminating positive contingencies relies on coding the co-occurrence of two target stimuli such that these are easier to detect compared to negative contingencies because of a higher number of cue-outcome pairs (higher frequencies of a and d) which facilitate reaching a judgment [7–8]. In contrast, discrimination of negative contingencies is relatively demanding because these require being aware that one event (cue or outcome) is absent when the other is present (higher frequencies of b and c) [7–8]. These studies suggest that thinking-related areas may become more active when people evaluate a negative contingency as participants allocate more attentional resources [7–8]. Taken together, it seems likely that the allocation of attention is sensitive to frequency of contingency ( $\Delta P$ ) whether it constitutes a negative, zero or positive relationship.

These behavioural findings raise the question about the functional neuroanatomical correlates of negative, zero and positive contingencies. Do these varied contingencies activate the same or different brain areas? Previous research generally focused on the relation between an action and reward based on conditional probabilities (e.g., manipulation in probability of b and c pairings in the zero contingency only) rather than establishing a relation between two events with negative, zero and positive frequency of contingency. These studies suggested the learning process is associated with activation of the frontoparietal network (e.g., inferior frontal gyrus (IFG), superior frontal gyrus (SFG), medial frontal areas (MedFG)), and more posterior areas such as inferior parietal lobule (IPL), posterior cingulate (PC), striatum, and caudate body [4,9–14]. Further, it has been shown that activations in certain areas (e.g. MedFG, IFG) differentiate in line with probability manipulations in tasks that establish a relation between the number of button presses and earning money [4,10–11]. Although these studies can be informative about brain systems and related processes, they are limited in addressing the question of whether contingencies with varied frequencies ( $\Delta P$  values) activate shared or different brain regions.

One study has explored the neural dynamics of contingency judgements with different  $\Delta P$  values using event related potentials (ERP) [4]. The authors employed the streaming paradigm introduced by Crump and colleagues [1,5] where participants viewed rapid presentations of emoticons as cue-outcome combinations. At the end of each stream, participants were required to predict the relationship between cue and outcome on a scale ranging from –100 to +100 (positive values indicating a positive relationship, 0 indicating no relationship, and negative values a negative relationship). The results demonstrated that attentional related areas negatively correlated with  $\Delta P$  with stronger activations in negative contingency conditions compared to the positive contingencies. Of note is that the study used emoticons as cue-outcome pairs - these contain emotional content which may activate similar regions to real emotional faces. Given this potentially confounding factor,

we wanted to explore the neuroanatomical correlates of contingency judgements with neutral (non-emotional) stimuli.

The present study utilizes fMRI to explore the neural substrates of contingency judgments across three contingency frequencies with negative, zero and positive  $\Delta P$  values, all derived from the same basic streaming paradigm [1,5], and using neutral stimuli as cue and outcome. More specifically, we were interested in assessing distinct regional brain activations across three contingency frequencies as well as the ones that they have in common. We propose that due to the involvement of attentional processes frontal areas may be differentially activated in negative contingencies compared to positive and zero whereas all three contingencies may activate some common overlapping areas in parietal regions.

## 2. Methods

### 2.1. Participants

Twenty healthy university students aged 18–30 (9 females:  $M = 20.55$ ,  $SD = 3.39$ ; 11 males:  $M = 22.72$ ,  $SD = 3.11$ ) took part in the study, giving informed consent beforehand. The participants had no psychiatric or neurological disorders based on a self-report questionnaire and received £30 for participation. The study was approved by the Ethics Committee at Brunel University London.

### 2.2. Task and procedure

The experiment utilized a streaming paradigm [1,5] with presentation and responses controlled by PsychoPy3 [15]. The stimuli used were triangles (the cue, C) and hexagons (the outcome, O) of approximately similar sizes. Trials in a stream (block) began with a central fixation cross (250 ms) followed by a presentation of C (250 ms) displayed on the left side of the screen, or with a blank screen (250 ms) reflecting -C. After that, either O appeared on the right side (500 ms), or a blank screen was shown (500 ms) reflecting -O. Each trial therefore lasted 1000 ms. There were three contingency learning conditions and a resting baseline condition (no stimuli or task). The contingency learning conditions were positive ( $\Delta P = 0.50$ ), zero ( $\Delta P = 0.0$ ) and negative contingencies ( $\Delta P = -0.50$ ), each block containing 16 trials. Before each block, instructions for the upcoming task was presented for 5 s; following each block a scale was presented to record responses (5 s, see below). Total block length was 26 s with each condition presented eight times in a randomized order. Six other conditions were presented, which are not relevant to this study.

### 2.3. MRI procedure

Imaging was carried out using a 3 T scanner (Trio, Siemens) equipped with a 32-channel array head coil. Participants lay supine in the scanner with cushions to reduce head motion. 35 axial slices ( $192 \times 192$  mm FOV,  $64 \times 64$  matrix,  $3 \times 3 \times 3$  mm voxels, interleaved slice acquisition) were acquired using a BOLD-sensitive gradient-echo *EPI* sequence (TR 2.5 s, TE 31 ms,  $85^\circ$  flip angle). High-resolution whole-brain images were acquired from each participant using a T1-weighted MPRAGE sequence (TR 1900 ms, TE 3.03 ms,  $11^\circ$  flip angle, 176 slices,  $1 \times 1 \times 1$  mm voxels). Participants viewed the stimuli via a mirror system while holding two MRI compatible response pads. After each block participants viewed a scale on the screen ranging from –4 to +4 making a single response using one of the two pads: The left-hand keypad for ratings from –4 (little finger) to 0 (thumb), right-hand keypad for +1 (index finger) to +4 (little finger). Participants were asked to predict how triangle predicts hexagon based on scale and following their response the next block started.

2.4. Data analyses

We used SPM12 for fMRI data analysis. The origins were manually aligned with the anterior commissure in structural and functional images. To correct head motion, realign & unwarp options were applied. All images were transformed into MNI space using normalization and unified segmentation. A Gaussian filter (FWHM 8 mm) was used for spatially smoothing functional data. The general linear model was used for statistical analysis based on a voxel-wise least-squares estimation for serially autocorrelated observations. Utilizing a blocked design approach, the BOLD response model was derived using a boxcar function, convolved with a canonical HRF without derivatives. Low-frequency noise was removed through high-pass filtering (cut-off frequency 1/128 Hz). To enable comparison across different contingency tasks, we modelled only the last 21 s of each block for all conditions (i.e. stimulus and response). The 5 s instruction period was modelled as a regressor of no interest.

Contrast of interests were first calculated for each individual participant. In the second-level analysis, we used a one-sample *t*-test to establish contingency-related activations.

In the conjunction analysis, we calculated the contrast of interests for negative, zero, and positive contingency streams separately i.e., (Negative contingency – Resting baseline), (Zero contingency – Resting baseline), and (Positive contingency – Resting baseline). All resulting *t*-maps were thresholded at the voxel level with *p* < 0.05 (FWE corrected, 3 3 3 mm<sup>3</sup> voxel size). Conjunction analyses were carried out for the three contrasts using the minimum statistics approach.

In the interaction analysis, we first calculated six subtraction contrasts to obtain contingency-related activation differences across Δ*P* manipulation: Negative contingency – Positive contingency, Negative contingency – Zero contingency, Zero contingency – Positive contingency and their reversed versions. Second-level results were examined with cluster-level corrections for multiple comparisons (uncorrected cluster-forming threshold of *p* < 0.005 and a family-wise error corrected cluster-level (FWEc) threshold of *p* < 0.05). Given the stimulus/task uniformity, we propose that activation derived from these subtractions cannot simply be explained by stimulus or response mechanisms.

3. Results

3.1. Behavioural results

To test whether the participants accurately discriminated contingencies, we calculated an ANOVA with the within-subject factor (negative, zero and positive contingencies). For the judgement ratings, we averaged the ratings of each type of contingency. Participants ratings increase as Δ*P* increases from negative to zero and to positive (main effect contingency; *F*(2,18) = 21.69*p* < 0.001),  $\eta^2 = 0.68$  (Fig. 1). More

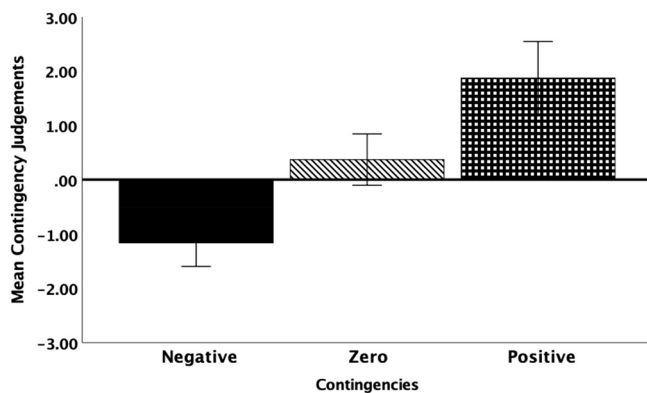


Fig. 1. Participant mean contingency judgements for different contingency frequencies (negative, zero and positive). Error bars indicate SEM.

precisely, the Bonferroni analysis demonstrated that positive contingencies were discriminated from negative (M difference = 3.1 (95 % CI, 4.10 to 2.45) and, zero contingencies (M difference = 1.50 (95 % CI, 2.23 to 0.84). Similarly, zero contingencies were discriminated from negative contingencies (M difference = 1.53 (95 % CI, 2.53 to 0.48), together indicating that participants were able to discriminate contingencies. Finally, as the average of zero contingencies were rated slightly positive, we calculated one sample *t*-tests to examine whether the average ratings were significantly different from zero. The results demonstrated that for all contingencies this was the case (Negative contingencies: *t*(19) = -20.36, *p* < 0.001, Zero contingencies *t*(19) = 6.00, *p* < 0.001, Positive contingencies *t*(19) = 22.86, *p* < 0.001).

3.2. Neuroimaging results

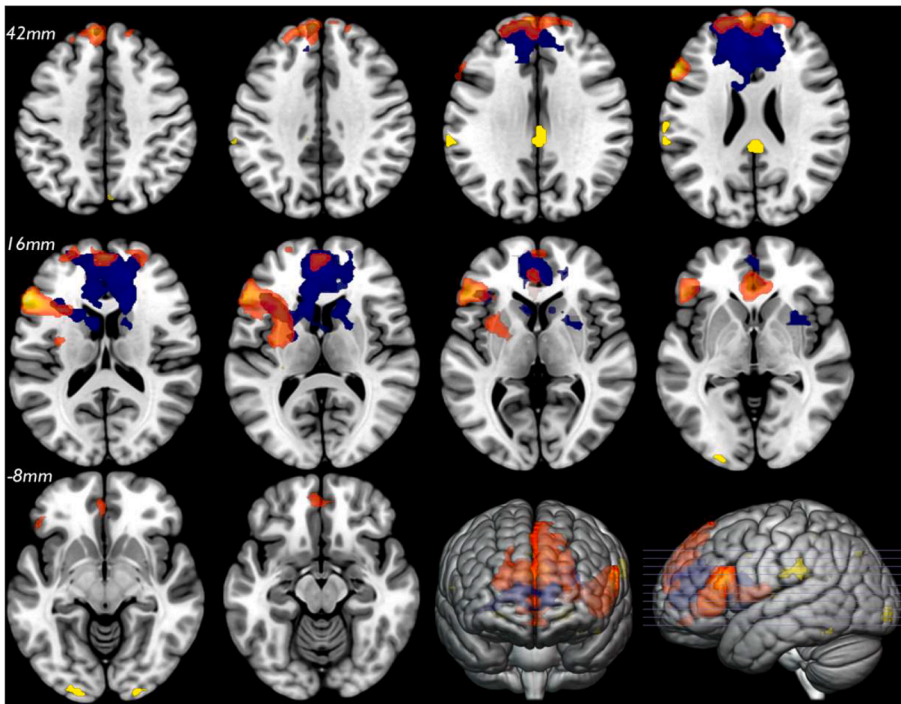
To determine the common cerebral areas activated by all three contingency frequencies, a conjunction analysis was carried out in which the changes in activity common to the comparison of the three versus baseline was assessed. This analysis showed shared areas with increased activity mainly in the left hemisphere in two clusters (Table 1). The first cluster included posterior cingulate gyrus (PC, BA23) while the second cluster included inferior parietal lobule (IPL, BA40), supramarginal gyrus (SMG) and superior temporal gyrus (STG, BA42) (Table 1, Shared Areas; Fig. 2, yellow patches).

Another question of interest concerned the brain activity unique to each individual contingency judgment process which we identified on the basis of brain activity that was differentially activated by only one contingency frequency compared to one other during the judgment processes. Of the six comparison contrasts, the contrast comparing negative, and zero contingencies revealed one large significant cluster covering IFG (BA 45) and MedFG (BA 9/10) in the left lateral and medial prefrontal areas (Table 1; Fig. 2, blue patches). A second contrast

Table 1

Coordinates of significant clusters common to all three contingency frequencies (Shared Areas) as well as those unique to individual contingency judgements (see Methods for details). Coordinates are reported in relation to the MNI space.

Anatomical area	BA	x y z	t/p (uncorr)	Cluster-level p (FWE)	Num. Voxels
Shared Areas					
Cluster 1					
PC	23	-3 -34 28	7.38/0.001	0.001	581
Cluster 2					
IPL	40	-63 -40 23	6.63/0.001	0.014	479
SMG	40	63 -34 23			
STG	42	-63 -31 18			
Negative – Zero					
Cluster 1					
MedFG	9/10	15 38 23	5.54/0.0001	0.001	1679
IFG	45	-39 23 11			
MedFG	9	-9 44 23			
Negative – Positive					
Cluster 1					
IFG	45	-57 23 20	4.67/0.0001	0.04	581
IFG	44	-48 20 17			
IFG	45	-51 26 2			
Cluster 2					
MedFG	9/10	-6 59 32		0.02	792
SFG	10	-18 59 23			
SFG	9	-9 50 44			



**Fig. 2.** Significant clusters of activity common to all three contingency frequencies (Negative, Zero, Positive) shown in yellow ( $p < 0.05$ , FWE corrected). The comparison contrasts that show differences between negative and zero contingency is shown in blue; differences between negative and positive contingency is in red (uncorrected cluster-forming threshold of  $p < 0.005$  and a family-wise error corrected cluster-level (FWEc) threshold of  $p < 0.05$ ). Data is superimposed on an MNI template brain.

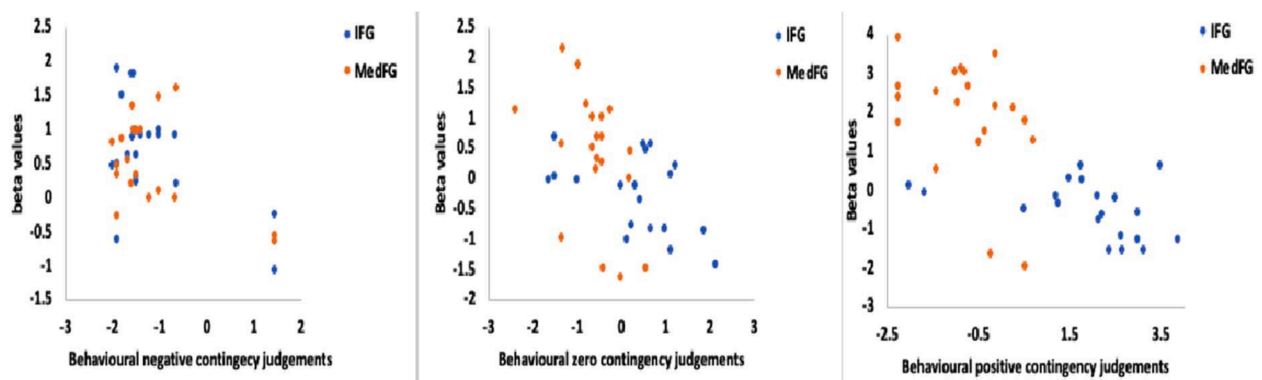
comparing negative and positive contingencies revealed significant activations in two clusters in the left lateral and medial frontal cortices. The cluster in the left lateral prefrontal cortices mainly included inferior frontal gyrus (BA 45/44), the second cluster in the medial frontal cortices covered MedFG (BA 9/10) and SFG (BA 9/10) (Table 1; Fig. 2, red patches). The remaining four contrasts, including the comparison between zero and positive contingencies, did not show significant activation.

Finally, we extracted the beta values around the group peak coordinate over IFG and MedFG and examined the correlation between behavioural performance and activations (Fig. 3). The results showed significant correlations between behavioural responses of negative contingencies and beta values from left IFG  $r = 0.52, p < 0.05$  and MedFG  $r = 0.46, p < 0.05$ . Moreover, we observed significant correlation between behavioural responses of zero contingency and left MedFG activations ( $r = -0.43, p < 0.05$ ) and positive contingencies and left IFG ( $r = -0.57, p < 0.05$ ). Similar patterns of results were observed for positive contingencies and MedFG as well as zero contingencies and IFG, but results did not reach statistical significance.

#### 4. Discussion

Our behavioural findings demonstrated that participants discriminated negative, zero and positive contingencies from each other as evidenced by higher ratings as  $\Delta P$  increased. The neuroimaging results showed shared areas mainly in the left parietal and temporal cortices including STG, IPL as well as PC that activated for the three contingencies (negative, zero and positive). Unique areas of activity were mainly evident for negative contingencies compared to positive and zero contingencies in the lateral and medial prefrontal cortices including IFG, MedFG and SFG.

The shared activity (i.e., IPL, SPL, PC and STG) observed in the current study for judgment of three contingencies suggests a potential common mechanism. Previous research suggested that most of these areas are activated in a wide range of attention related tasks for coding, maintenance and integration of information serving in a domain-free capacity not exclusively linked to specific tasks [10,16–17]. In the context of contingency judgements, it has been suggested that these regions are involved in coding the value of outcomes related to a potential cue in animals [18] as well as in humans [19]. It has been shown both frontal and parietal regions are involved in contingency learning,



**Fig. 3.** demonstrate behavioural responses and beta activities across negative, zero and positive contingencies in scatter plots.

but these regions differ regarding their roles [18,20]. While the parietal areas are involved in information integration and acquisition of the associative relations, prefrontal regions are involved in supervising of these contingency judgements [18]. For instance, the posterior cingulate cortex has reciprocal connections with all sensory cortices making it an ideal region for the integration of information [24]. Moreover, human studies showed that areas of the parietal lobe such as the posterior cingulate cortex, inferior parietal lobule as well as superior temporal gyrus are involved in conditioning and establishing causal relationships [21–23]. Our findings are consistent with those previous studies and further indicate that these activated areas may be involved in contingency judgments regardless of  $\Delta P$  manipulation. It seems likely that whatever the relation between cue and outcome, a common mechanism is needed to integrate and update information for establishing a judgment because any contingency judgment process requires assessment of the contingency that involves integration and updating of the information [18,20]. However, despite of this consistency, the caution is advised as we did not use a control task in the analysis that may leads involvement of stimuli/response areas in the observed findings.

We found differential activations in negative contingencies compared with positive and zero contingencies in attention related prefrontal areas. These results are consistent with an ERP study [8] that reported stronger activity in attention related areas during discrimination of negative contingencies compared with positive and zero contingencies. It was suggested that establishing a prediction is easier during the process of positive contingencies compared to negative ones because there is consistency between pairs of cue and outcome [7]. Such a co-occurrence and co-absence of cue-outcome pairs may allow a more automatic establishment of a link between cue and outcome [7]. In contrast, it's harder to conceptualise that the presence of a cue means absence of an outcome and vice versa [7]. Therefore, discriminating negative contingencies are more demanding since these processes involve being aware of the absence of an event while the other is present and such a process may require investment of more attentional resources into the task rather than an automatic development [7].

It is worth noting the observation that increased activations in IFG and MedFG have been repeatedly reported to be involved in contingency learning process for supervising and computation of contingencies [10–11] as well as working memory for resolution of conflicts representing inhibition function [24]. Therefore, the inconsistency between occurrence of cue and outcome (i.e., higher frequencies of b and c pairings) may lead to a greater involvement of inhibitory control to identify negative contingencies accurately. In line with this argument, one study demonstrated that when participants judge an inconsistent relation between cue and outcome such as evaluation of an implausible statement with a strong theory, attention related areas activated strongly [25]. Taken together, activating representation of a consistency between cue and outcome and activating representation of the inconsistency between cue and outcome may differentiate – the latter may activate working memory areas more strongly.

Although the activations in comparison of negative-zero and negative-positive look different, more detailed scrutiny reveals that there is some overlap (see Fig. 2). Consistent with the frequencies of b and c in each contingency, the activations for comparison of negative and positive contingencies were larger than the comparison between negative and zero. Therefore, the relationship between the frequencies of a-d, performance, and brain activations across different  $\Delta P$  values suggests that contingency judgement influences the neurocognitive processing of judgement gradually.

We did not find a significant difference between judgements of positive and zero contingencies. The current study cannot answer whether this is caused by a lack of statistical power or whether zero contingencies are associated with an optimistic perspective where they are perceived slightly positive. Nevertheless, examining our behavioural results, the average ratings of zero contingency were slightly but significantly greater than zero. Therefore, participants may perceive the

contingency to be slightly positive. Previous research reported that healthy participants may perceive zero contingencies as positive (26). As our sample consisted of similarly healthy participants, they may have perceived zero contingencies as positive leading to non-significant results. Alternatively, our relatively small sample size may have contributed to this finding (20 participants), or the discrete sampling of the  $\Delta P$  scale (three unique contingencies,  $\Delta P = -0.50, 0, +0.50$ ) may not be sufficiently distributed.

To conclude, we found participants were able to discriminate between three contingencies accordingly (negative, zero and positive); we also showed shared activations for these contingencies as well as distinct areas for negative compared to positive and zero contingencies. We interpret the finding as evidence that the shared regions may be involved in coding, integration and updating of associative relations and distinct regions may be involved in investment of attentional resources to a varied extent in the computation of contingencies to make a judgement. As the current study used fixed  $\Delta P$ s (-0.50, 0, 0.50) across all tasks, future studies should focus on using multiple  $\Delta P$ s for each contingency with greater sampling to confirm the current findings.

#### Data availability

Data, stimuli and other materials are available on: [https://figshare.com/articles/dataset/functional\\_neuroanatomical\\_correlates\\_of\\_contingency\\_judgment/19768618](https://figshare.com/articles/dataset/functional_neuroanatomical_correlates_of_contingency_judgment/19768618).

#### CRediT authorship contribution statement

**Rahmi Saylik:** Software, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Visualization. **Andre J. Szameitat:** Software, Writing – review & editing, Visualization. **Adrian L. Williams:** Conceptualization, Methodology, Writing – review & editing. **Robin A. Murphy:** Supervision, Software, Formal analysis, Investigation, Methodology, Writing – review & editing, Visualization.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

[https://figshare.com/articles/dataset/functional\\_neuroanatomical\\_correlates\\_of\\_contingency\\_judgment/19768618](https://figshare.com/articles/dataset/functional_neuroanatomical_correlates_of_contingency_judgment/19768618)

#### References

- [1] M.J.C. Crump, S.D. Hannah, L.G. Allan, L.K. Hord, Contingency judgements on the fly, *Q. J. Exp. Psychol.* 60 (6) (2007) 753–761.
- [2] Pearce JM, Mackintosh NJ. Two theories of attention: A review and a possible integration. *Atten Assoc Learn From brain to Behav.* 2010;11–39.
- [3] T. Tsukiura, M. Namiki, T. Fujii, T. Iijima, Time-dependent neural activations related to recognition of people's names in emotional and neutral face-name associative learning: an fMRI study, *Neuroimage.* 20 (2) (2003) 784–794.
- [4] S.C. Tanaka, B.W. Balleine, J.P. O'Doherty, Calculating consequences: brain systems that encode the causal effects of actions, *J. Neurosci.* 28 (26) (2008) 6750–6755.
- [5] S.D. Hannah, M.J.C. Crump, L.G. Allan, S. Siegel, Cue-interaction effects in contingency judgments using the streamed-trial procedure, *Can J. Exp. Psychol.* [Internet]. 63 (2) (2009) 103–112, <https://doi.org/10.1037/a0013521>. Available from:.
- [6] A. Maldonado, A. Catena, J.C. Perales, A. Cándido, Cognitive Biases in Human Causal Learning, *10 (2) 2007 pp.* 242–250.
- [7] A. Maldonado, G. Jiménez, A. Herrera, J.C. Perales, A. Catena, Inattention blindness for negative relationships in human causal learning, *Q J. Exp. Psychol.* 59 (3) (2006) 457–470.
- [8] J.J. Heisz, S. Hannah, J.M. Shedden, L.G. Allan, Neural temporal dynamics of contingency judgement, *Q. J. Exp. Psychol.* 64 (4) (2011) 792–806.
- [9] D.D. Cummins, Neural correlates of causal power judgments, *Front Hum. Neurosci.* 8 (2014) 1014.
- [10] M. Liljeholm, E. Tricomi, J.P. O'Doherty, B.W. Balleine, Neural correlates of instrumental contingency learning: Differential effects of action-reward conjunction and disjunction, *J. Neurosci.* 31 (7) (2011) 2474–2480.

- [11] M. Liljeholm, S. Wang, J. Zhang, J.P. O'Doherty, Neural correlates of the divergence of instrumental probability distributions, *J. Neurosci.* 33 (30) (2013) 12519–12527.
- [12] J. Van Dessel, M. Danckaerts, M. Moerkerke, S. Van der Oord, S. Morsink, J. Lemièr, E. Sonuga-Barke, Dissociating brain systems that respond to contingency and valence during monetary loss avoidance in adolescence, *Brain Cogn.* 150 (2021) 105723.
- [13] E.T. Rolls, W. Cheng, J. Feng, The orbitofrontal cortex: reward, emotion and depression, *Brain Commun.* 2(2):fcaa196 (2020).
- [14] H.J. Spiers, B.C. Love, M.E. Le Pelley, C.E. Gibb, R.A. Murphy, Anterior temporal lobe tracks the formation of prejudice, *J. Cogn. Neurosci.* 29 (3) (2017) 530–544.
- [15] J. Peirce, J.R. Gray, S. Simpson, M. MacAskill, R. Höchenberger, H. Sogo, E. Kastman, J.K. Lindeløv, PsychoPy2: Experiments in behavior made easy, *Behav. Res. Methods.* 51 (1) (2019) 195–203.
- [16] M. Liljeholm, Neural Correlates of Causal Confounding, *J. Cogn. Neurosci.* 32 (2) (2020) 301–314.
- [17] R. Saylik, A.L. Williams, R.A. Murphy, A.J. Szameitat, Characterising the unity and diversity of executive functions in a within-subject fMRI study, *Sci. Rep.* 12 (1) (2022).
- [18] T.J. Bussey, J.L. Muir, B.J. Everitt, T.W. Robbins, Triple dissociation of anterior cingulate, posterior cingulate, and medial frontal cortices on visual discrimination tasks using a touchscreen testing procedure for the rat, *Behav. Neurosci.* 111 (5) (1997) 920.
- [19] B.J. Levy, A.D. Wagner, Cognitive control and right ventrolateral prefrontal cortex: reflexive reorienting, motor inhibition, and action updating, *Ann. N.Y. Acad. Sci.* 1224 (1) (2011) 40–62.
- [20] B.Y. Hayden, A.C. Nair, A.N. McCoy, M.L. Platt, Posterior cingulate cortex mediates outcome-contingent allocation of behavior, *Neuron.* 60 (1) (2008) 19–25.
- [21] P.C. Fletcher, J.M. Anderson, D.R. Shanks, R. Honey, T.A. Carpenter, T. Donovan, N. Papadakis, E.T. Bullmore, Responses of human frontal cortex to surprising events are predicted by formal associative learning theory, *Nat. Neurosci.* 4 (10) (2001) 1043–1048.
- [22] D.C. Turner, M.R.F. Aitken, D.R. Shanks, B.J. Sahakian, T.W. Robbins, C. Schwarzbauer, et al., The role of the lateral frontal cortex in causal associative learning: exploring preventative and super-learning, *Cereb Cortex.* 14 (8) (2004) 872–880.
- [23] A.R. Aron, The neural basis of inhibition in cognitive control, *Neuroscientist.* 13 (3) (2007) 214–228.
- [24] J.A. Fugelsang, K.N. Dunbar, Brain-based mechanisms underlying complex causal thinking Brain-based mechanisms underlying complex causal thinking. 43 (8), 2005 pp. 1204-1213.
- [25] R.M. Msetfi, R.A. Murphy, J. Simpson, Depressive realism and the effect of intertrial interval on judgements of zero, positive, and negative contingencies, *Q. J. Exp. Psychol.* 60 (3) (2007) 461–481.