What is the evidence for quantum like interference effects in perception?

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Abstract

This paper examines the empirical evidence for interference effects in perceptual experiments. It also reviews the competing interpretation of the effects with respect to traditional cognitive models and new quantum cognition models. The conclusion is that better experiments with more conditions are needed to provide stronger empirical tests of the competing models.

Recently researchers have reported evidence for 'quantum like' interference effects in perception, and this evidence is then used to justify the development of 'quantum wave like' representations of the experimental results (Khrennikov, 2010). What is an interference effect, what is the empirical evidence for these effects, what is the best explanation for these effects, and what direction should we take next? We intend to answer these four questions in this paper.

1 What is an interference effect?

Suppose we have two different perceptual judgment tasks: one labeled task A and the response to this task is measured by J different levels of a response variable (e.g. $J = 2$ binary forced choice); another is task B with K levels of a response measure (e.g. $K = 7$ point confidence rating). Participants are randomly assigned to two groups: one group of participants (group B) recieves only task B, but the other group (group AB) receives task A followed immediately by task B. (Other variations are of course possible, such as presenting both tasks in different counterbalanced orders, but let us focus on this simple design).

From this experiment we obtain proportions which are estimates of the response probabilities, which includes (a) the probability of choosing level k from the response to task B from group B-alone symobized as $p_B(R_B = k)$, (b) the probability of first responding with level j from task A, denoted $p_{AB}(R_A = j)$, and (c) the probability of responding with level k from task B given that the person responded with level j on the earlier task A, denoted $p_{AB}(R_B = k|R_A = j)$. From the latter two probability distributions we can compute the total probability for response to task B as

$$TP(R_B = k) = \sum_{j=1}^{K} p_{AB}(R_A = j) \cdot p_{AB}(R_B = k|R_A = j).$$

The interference effect for level k of the response to task B (produced by responding to task A) equals by definition

$$Int_B(k) = p_B(R_B = k) - TP(R_B = k).$$

Note that $\sum_{k=1}^{K} p_B(R_B = k) = 1 = \sum_{k=1}^{K} TP(R_B = k)$ so that $\sum_k Int_B(k) = 0$. Interference effects frequently occur in particle physical experiments, such as the findings from the famous two slit experiment. These interference effects obtained with single particles prompted the creation of the 'particle - wave' theory of quantum mechanics.

First we simply ask – do these interfence effects occur in human perceptual studies? If they do, there may be many easy explanations such as learning effects and practice and boredom effects, ect. So below we examine two studies in which these simple reasons to not seem to exist. The experiments reported below using only $J = 2$ and $K = 2$ levels (e.g. a binary choice is made for each task). In this case we can obtain only one interference effect (the other is the negative of the first).

2 What is the evidence for interference effects?

2.1 Studies by Conte et al.

Interference effects were first found found in a series of three experiments on perceptual judgment tasks with ambiguous figures (Conte et al., 2009).[1] Each study included approximately 100 students randomly divided into two groups: In group A-Alone, each person was given 3 seconds to make a single binary choice concerning an ambiguous figure B (+ indicates one alternative, − indicates the other alternative); in group BA, each person was given 3 seconds to make a single binary choice for an ambiguous figure B followed 800 msec later by a 3 second presentation requesting another single binary choice for figure A. In the first experiment, stimulus A was two horizontal lines of equal length placed in a context creating an illusion that one line was longer than another; stimulus B was two non overlapping circles of equal radius placed in a context creating an illusion that one circle was larger than another; the task was to decide whether the objects were equal or not. In the second experiment, stimulus A was a Rubin type ambiguous figure, and stimulus B was a completely different Rubin type ambiguous figure; and the task was to choose one of the two possible interpretations of the ambiguous figure. The third experiment used a Stroop task with animals of different sizes (e.g., big mouse, small lion) and the task

[1] Actually four experiments were conducted but the second and third only differed by changing the roles of the stimuli assigned to A and B, the results were very similar, and so I collapsed data across these two experiments.

was to choose the larger object. The results are shown in Table 1 below. As can be seen in this table, all three groups produced significant interference effects (using a z test for the difference). Surprisingly the direction changed across experiments.

Table 1: Results from Elio Conte Experiments

$p(B+)$	$p(A+\|B+)$	$p(B-)$	$p(A+\|B-)$	$TP(A+)$	$p(A+)$	z	p
0.5556	0.6000	0.4444	0.3750	0.5000	0.6667	2.0287	0.0425
0.6207	0.7776	0.3793	0.5425	0.6884	0.5517	-2.1448	0.0320
0.3529	0.1667	0.6471	0.6364	0.4706	0.6471	2.0722	0.0382

N = number of observations per group

2.2 Studies by Wang, Busemeyer, Townsend

Townsend (Townsend, Silva, Spencer-Smith, & Wenger, 2000) introduced a new paradigm to study the interactions between categorization and decision making, which we discovered is highly suitable for investigating interference effects. On each trial, participants were shown pictures of faces, which varied along two dimensions (face width and lip thickness). Two different distribution of faces were used: on average a 'narrow' face distribution had a narrow width and thick lips; on average a 'wide' face distribution had a wide width and thin lips. The participants were asked to categorize the faces as belonging to either a 'good' guy or 'bad' guy group, and/or they were asked to decide whether to take a 'attack' or 'withdraw' action. The participants were informed that 'narrow' faces had a .60 to come from the 'bad guy' population, and 'wide' faces had a .60 chance to come from the 'good guy' population. The particants were usually rewarded for attacking 'bad guys' and they were usually rewarded for withdrawing from 'good guys.' The primary manipulation was produced by using the following four test conditions, presented across a series of trials, to each participant. In the C-then-D condition, participants made a categorization followed by an action decision; in the D-Alone condition, participants only made an action decision.

The categorization-decision paradigm provides a simple test of the law of total probability. In particular, this paradigm allows one to compare the probability of taking an 'attack' action obtained from the D-Alone condition with the total probability computed from the C-then-D condition. Townsend et al. (2000) reported chi square tests at the .05 significance level. They found that with narrow faces, 38 out of 138 participants produced statistically significant deviations; with wide faces, 34 out of 138 did so. These numbers are much higher than what is expected by chance alone (using a significance level at .05 the expected number is only $(.05)(138) = 6.9$).

Townsend et al. did not report the direction of the interference effects, and only reported the chi square magnitudes. To determine the direction of the interference effects, Wang (Busemeyer, Wang, & Lambert-Mogiliansky, 2009) conducted a replication of the Townsend study using 26 participants, but each participant provided 51 observations for the C-D condition for a total of $26 \times 51 = 1326$ observations, and each person produced 17 observations for the D-alone condition producing $17 \times 26 = 442$ total observations. The results are shown in Table 2.

Table 2: Category-decision making task results

Type Face	$p(G)$	$p(A\|G)$	$p(B)$	$p(A\|B)$	TP	$p(A)$	t	p
Wide	.84	.35	.16	.52	.37	.39	.5733	.5716
Narrow	.17	.41	.83	.63	.59	.69	2.54	.018

The column labeled $p(G)$ shows the probability of categorizing the face as a 'good guy,' the column labeled $p(A|G)$ shows the probability of attacking given that the face was categorized as a 'good guy,' the column $p(A|B)$ shows the probability of 'attacking' given that the face was categorized as a 'bad guy,' the column TP shows the total probability, and the column $p(A)$ shows the probability of 'attack' when this decision was made alone. The results for both faces produce some deviation between TP and $p(A)$ but the most pronounced deviation occurred for the narrow faces. Surprisingly, interfernce effect was statistically significant for the narrow faces, but not for the wide faces (using a paired t-test).

3 What are explanations for these effects?

Interference effects are simply empirical results that need a scientific explanation. One cannot immediately jump to the conclusion that they are evidence for quantum mechanisms, nor can one jump to the conclusion that they are easily explained without quantum theory. Psychologists often like to explain results using intuitive conceptual ideas such as 'interference effects simply result from the first question producing a context that affects the second question.' Maybe this serves as a description of the results, but intuitive explanations such as this can be formulated mathematically as either a classic or a quantum model, and so they do not discriminate between these two theoretical competitors. The scientific way to determine whether the data follow quantum or classical probability rules is derive formal predictions from each theory and then compare the predictions with the data. Let us focus on teh categorization - decision making task and consider a few standard models for this task.

Townsend et al. originally proposed a Markov model for the task: the person starts in a state determined by the face. Then there is a probability of transiting to the 'good guy' category and another probability $p(B|F) = 1 - p(G|F)$ of transiting to the category 'bad guy.' On the one hand, if the state transits to 'good guy' then there is a probability $p(A|G)$ of attacking, and probability $p(W|G)$ of withdrawing. On the other hand, if the state transits to the 'bad guy' category, then there is a probability $p(A|B)$ of attacking and another probability $p(W|B)$ of withdrawing. This model satisfies the law of total probability (which is essentially the Chapman - Kolmogorov equation for Markov processes)

$$p(A|F) = p(G|F) \cdot p(A|G) + p(B|F) \cdot p(A|B)$$

and so it cannot explain the interference effect.

Another classic psychology model is the multidimensional signal detection model used in general recognition theory (Ashby & Townsend, 1986). According to this theory, on each trial, the presentation of a face produces a perceptual image, which is represented as a point within a two multidimensional (face width, lip thickness) perceptual space. Furthermore, each point in the perceptual space is assigned to a 'good' guy (denoted G) or 'bad' guy (denoted B) category response label; and at the same time, each point is also assigned a 'withdraw' (denoted W) or 'attack' (denoted A) action. Let $G\&W$ represent the set of points in the space that are assigned to the 'good' guy category and the 'withdraw' action; and analogous definitions apply to form the sets $G\&A$, $B\&W$, and $B\&A$. Thus the probability of categorizing the face as a 'good guy' and taking a 'withdraw' action, denoted $p(G\&W)$, equals the probability of sampling a face that belongs to the $G\&W$ set of points; the other three probabilities, $p(G\&A)$, $p(B\&W)$, and $p(B\&A)$, are determined in an analogous manner. But once again, the marginal probability of taking a 'defensive' action is determined by the *law of total probability*:

$$p(A) = p(G\&A) + p(B\&A) = p(G) \cdot p(A|G) + p(B) \cdot p(A|B).$$

What is a quantum model for this task? A simple one is the following: the person starts in a state $|F\rangle$ determined by the face. Then there is an amplitude $\langle G|F\rangle$ of transiting to the 'good guy' category and another amplitude $\langle B|F\rangle$, $|\langle G|F\rangle|^2 + |\langle B|F\rangle|^2 = 1$, transiting to the 'bad guy' category. One the one hand, if the state transits to the 'good guy' then there is an amplitude $\langle A|G\rangle$ of transiting to the 'attack' action and another amplitude $\langle W|G\rangle$, $|\langle A|G\rangle|^2 + |\langle W|G\rangle|^2 = 1$, of transiting to the 'withdraw.' On the other hand, if the state transits to the 'bad guy' category, then there is an amplitude $\langle A|B\rangle$ of transiting to the 'attack' action and another amplitude $\langle W|B\rangle$, $|\langle A|B\rangle|^2 + |\langle W|B\rangle|^2 = 1$, of transiting to the 'withdraw.' According to quantum probability theory, the total probability for attack (after first resolving the category) is computed the same as before

$$TP = |\langle A|G\rangle|^2 \cdot |\langle G|F\rangle|^2 + |\langle A|B\rangle|^2 \cdot |\langle B|F\rangle|^2 .$$

But the probability to attack (leaving the category unresolved) equals

$$\begin{aligned} p(A|F) &= |\langle A|F\rangle|^2 = |\langle A|I|F\rangle|^2 \\ &\quad |\langle A|G\rangle\langle G| + |B\rangle\langle B|F\rangle|^2 \\ &= |\langle A|G\rangle\langle G|F\rangle + \langle A|B\rangle\langle B|F\rangle|^2 \\ &= |\langle A|G\rangle|^2 \, |\langle G|F\rangle|^2 + |\langle A|B\rangle|^2 \, |\langle B|F\rangle|^2 \\ &\quad +2 \cdot |\langle A|G\rangle\langle G|F\rangle\langle A|B\rangle\langle B|F\rangle| \cdot \cos(\theta) \end{aligned}$$

This model satisfies the law of total amplitude and it violates the law of total probability. The last term is called the interference term which is used to explain interference effects.

Let us see how this works for the narrow face condition in which we observed the largest interference effect. Suppose we set $\langle A|G\rangle = \sqrt{.4} \cdot e^{i\cdot(.41\cdot\pi)}$ and then $\langle W|G\rangle = \sqrt{.6} = \langle A|B\rangle$ and we set $\langle G|F\rangle = \sqrt{.17}$ and then $\langle B|F\rangle = \sqrt{.83}$, then we almost exactly reproduce all the results for the narrow face in Table 2.

We have not proven that the quantum model is right, or even that the quantum model is better than all Markov models or all signal detection models. We could construct other higher dimensional Markov models to fit these results. We could also allow response boundaries to change across tasks in the signal detection models. Also this particular simple quantum model does not fit the wide face data quite as well as the narrow face data. The best we can do with the data so far is say that two of the most popular traditional models for this task (both based on classic probability theory) fail to explain the results. The simple quantum model can fit the narrow face data well but it fits the wide face data less well and so we could conclude that this simple quantum model is better than the simple Markov model or the signal detection model.

4 What next?

New research needs to be conducted that generates many more conditions for testing the competing models more rigorously. So far we can only post hoc fit parameters to the observed data and see if the fit is reasonable. What we need to do is make new apriori predictions for new conditions based on parameters estimated from previous conditions. For example, in the categorization - decision making task, we could manipulate the payoffs for attacking or withdrawing to generate many more conditions and the use these new conditions to perform stronger tests. Without these stronger apriori tests of the quantum or classic models, we are simply redescribing data with model parameters.

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