Special Issue on Computational Models of Classical Conditioning

Guest Editors' Introduction

After editing our respective books on computational models of conditioning (Schmajuk, 2010; Alonso & Mondragón, 2011) we started thinking about evaluating the performance of current computational models of classical conditioning by applying them to a common data base, and suggested this as the topic for a Special Issue of "Learning & Behavior".

In order to present the reader with a coherent issue rather than a disjointed collection of papers, we set three requirements for contributors to our project: models should be tested against a list of previously agreed phenomena; model parameters should be fixed across simulations; and authors should make available the simulations they used to test their models. In short, the models and their simulations should be replicable. These requirements of the project resulted in three major products:

1. The first is a list of fundamental classical conditioning results for which there is a consensus about their reliability. The list, shown in Table 1, is based on contributions from all members of the Society for Computational Models of Associative Learning (SOCMAL) (but special thanks go to Allan Wagner and Edgar Vogel). This list has acted to guide each of the papers that appear in this issue.

2. The second outcome of this project is that it provides the necessary information to evaluate each of the models. Although quantitative formulas can be used to evaluate models (based on deviations from predicted values, the number of data points and the number of free parameters [Akaike, 1974; Bunge, 1967; Schwarz, 1978]), to rely exclusively on such formalisms is not advisable – evaluating a model requires careful consideration of many

factors, both technical and formal (Baum, 1983). Wills and Pothos (2012) suggested that the competence of a model could be assessed by analyzing the number of “irreversible” successes in accounting for the experimental data. An irreversible success is one achieved by using a fixed set of model parameters that apply to all the phenomena that the model is intended to address. In order to obtain a simple comparable measure of success across models, Wills and Pothos (2012, p. 111) suggested adopting ordinal adequacy as the primary measure of a model success.

3. The third outcome is a repository of computational models ready to generate simulations. We felt strongly that, other considerations apart, the chief advantage of computational models derives from the simulations they yield. Implementing a model requires precise definitions – be these in the form of a specific programming language or of a formal model -- that makes the original psychological model “accountable”. Simulations allow us to execute calculations rapidly and, most importantly, accurately. Computation is critical, particularly when the models are described in non-linear equations, as is the case for those presented in this issue. Traditional methods used to test the predictive power of models, principally verbal intuitive reasoning, are not fit for the purpose. Perhaps more importantly, the outputs of a simulation provide feedback for the psychological models, thus becoming an essential part of the cycle of theory formation and refinement.

The knowledgeable reader will miss certain models no doubt; however we believe that the contents of this issue represent the state of the art in computational modeling of classical conditioning. We hope it provides a way to find promising avenues for future model development, and that it may serve as a starting point for discussion of where we stand and how to proceed towards a “Standard Model of Classical Conditioning." A future meeting of SOCMAL will be an ideal scenario to discuss these issues. Finally, we would like to thank the authors for their hard work, the twenty-one reviewers for their invaluable input, and Geoffrey Hall for his support.

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(Guest Editors)

Table 1. List of experimental results to be addressed by the models. GENERAL: Results that been demonstrated in a wide variety of procedures/ organisms. Good models of conditioning should be able to describe them. SOME DATA: Results that have not yet been demonstrated in a wide variety of procedures/ organisms. Models may or may not address these.

Phenomenon	Reference
1. Acquisition (6)	
1.1 Acquisition. After a number of CS-US pairings, the CS elicits a conditioned response (CR) that increases in magnitude and frequency.	GENERAL Pavlov (1927)
1.2. Partial Reinforcement. The US follows the CS only on some trials and might lead to a lower conditioning asymptote.	GENERAL Pavlov (1927)
1.3 US- and CS-specific CR. The nature of the CR is determined not only by the US but also by the CS.	SOME DATA Holland (1977)
1.4 Conditioned diminution of the UR. A trained CS can come to control an ability to diminish the response to the US with which it was trained.	GENERAL Kimble & Ost (1961) Kimmel (1966) Wagner, Thomas, & Norton (1967) Hupka, Kwaterski, & Moore (1970) Donegan (1981) McNish, Betts, Brandon, & Wagner (1997)
1.5. Divergence of Response measures. Different CRs established with the same US may show differential change with parametric variation in training.	GENERAL VanDercar & Schneiderman (1967) YeHLe (1968) Schneiderman (1972) Tait & Saladin (1986)
1.6.Conditioning proceeds more rapidly to cues previously experienced as imperfect predictors.	GENERAL Wilson, Boumphrey, & Pearce (1992)
2. Extinction (3)	
2.1 Extinction. The CR decreases when CS-US pairings are followed by presentations of the CS alone or by unpaired CS and US presentations.	GENERAL Pavlov (1927)
2.2 Partial reinforcement extinction effect (PREE). Extinction is slower following partial than	GENERAL

continuous reinforcement, if it occurs, is relatively fragile.	Thomas & Wagner (1964) Wagner, Siegel, Thomas, & Ellison (1964) Wagner, Siegel, & Fein (1967)
2.3 Changing the context in which extinction has occurred produces renewal of the CR, even if the change is to an equally nonreinforced context.	SOME DATA Harris, Jones, Bailey, & Westbrook (2000)
3. Generalization (3)	
3.1 Generalization. A CS2 elicits a CR to the degree that it shares some characteristics with a CS1 that has been paired with the US.	GENERAL Siegel, Hearst, George, & O'Neal (1968)
3.2 External inhibition. A special case of 3.1 where CS2 is CS1 with an added stimulus.	GENERAL Pavlov (1927)
3.3. Adding a cue to a trained compound results in a smaller decrease in CR than removing a cue from a trained compound.	GENERAL Brandon, Vogel, & Wagner (2000) González, Quinn, & Fanselow (2003)
4. Discriminations (17)	
4.1 When one CS is reinforced and another CS is nonreinforced, differential responding develops that is greater than that resulting from simple generalization between the two.	GENERAL Pavlov (1927)
4.2 Positive Patterning. Reinforced CS1-CS2 presentations intermixed with nonreinforced CS1 and CS2 presentations result in stronger responding to CS1-CS2 than to the sum of the individual responses to CS1 and CS2.	GENERAL Bellingham, Guillette-Bellingham, & Kehoe (1985)
4.3 Negative Patterning. Nonreinforced CS1-CS2 presentations intermixed with reinforced CS1 and CS2 presentations result in weaker responding to CS1-CS2 than to the sum of the individual responses to CS1 and CS2.	GENERAL Bellingham et al. (1985)
4.4 PP is easier than NP.	GENERAL Bellingham et al. (1985)
4.5 Adding a common cue to NP decreases discrimination.	GENERAL Redhead & Pearce (1998)
4.6 Patterning discriminations with 3 CS is learnable.	GENERAL Redhead & Pearce (1995) Myers, Vogel, Shin, & Wagner (2001)
4.7 Biconditional discrimination of the form AC+ AD- BC- BD+ is learnable.	GENERAL Saavedra (1975)
4.8 Biconditional discrimination is harder than NP.	SOME DATA Harris, Livesey, Gharaei, & Westbrook (2008)

4.9 Biconditional discrimination is harder than component discrimination of the form AC+ AD+ BC- BD-.	GENERAL Saavedra (1975)
4.10 Following A+/B+ and X-/Y- training, discrimination between compounds AY+ and AX- was solved relatively faster than the discrimination between compounds AY+ and BY-.	SOME DATA Haselgrove, Esber, Pearce, & Jones (2010)
4.11 Following AW+ and BX+, and non-reinforced CW- and DX - training (A, B, C, and D were colors and W and X were patterns), the AW+/AX- discrimination was learned slower than the AW+/BX- discrimination.	SOME DATA Dopson, Esber, & Pearce (2010)
4.12 Simultaneous Feature-positive Discrimination. Reinforced simultaneous CS1-CS2 presentations, alternated with nonreinforced presentations of CS2, result in stronger responding to CS1-CS2 than to CS2 alone. In this case, CS1 gains a strong excitatory association with the US.	GENERAL Ross & Holland (1981)
4.13 Serial Feature-positive Discrimination. Reinforced successive CS1-CS2 presentations, alternated with nonreinforced presentations of CS2, result in stronger responding to CS1-CS2 than to CS2 alone without CS1 gaining excitatory tendency.	GENERAL Ross & Holland (1981)
4.14 Simultaneous Feature-negative Discrimination. Non-reinforced simultaneous CS1-CS2 presentations, alternated with reinforced presentations of CS2, result in weaker responding to CS1-CS2 than to CS2 alone. In this case, CS1 gains a strong inhibitory association with the US.	GENERAL Holland (1984)
4.15 Serial Feature-negative Discrimination. Non-reinforced successive CS1-CS2 presentations, alternated with reinforced presentations of CS2, result in weaker responding to CS1-CS2 than to CS2 alone, without CS1 gaining inhibitory tendency.	GENERAL Holland (1984)
4.16 Feature positive discrimination is easier than feature negative.	GENERAL Hearst (1975) Reberg & LeClerc (1977)
4.17 In serial discrimination, one CS1 can be trained to concurrently serve as the feature in both a feature negative and a feature positive discrimination with different CS2s.	SOME DATA Holland (1991)
5. Inhibitory conditioning (6)	
5.1 Conditioned Inhibition. The inhibitory tendency controlled by CS1 results from a feature-negative discrimination (see 4.12) as revealed in summation and retardation tests.	GENERAL Pavlov (1927)
5.2 Contingency. A CS becomes inhibitory when the probability that the US will occur in the presence of the CS, p(US/CS), is smaller than the probability that the US will occur in the absence of	GENERAL Rescorla (1969)

the CS (p(US/noCS).	
5.3 Extinction of Conditioned Inhibition. Inhibitory conditioning is extinguished by CS2-US presentations, but not by presentations of CS2 alone.	GENERAL Rescorla (1969) Zimmer-Hart & Rescorla (1974)
5.4a Following conditioned inhibition, reinforced and non-reinforced presentations of excitor CS1 might modify the power of CS2 in summation tests.	GENERAL Rescorla & Holland (1977) Williams, Travis, & Overmier (1986) Amundson, Wheeler, & Miller (2005)
5.4b Following conditioned inhibition, reinforced and non-reinforced presentations of excitor CS1 might modify the power of CS2 in retardation tests.	Lysle & Fowler (1985)
5.5 Following conditioned inhibition, reinforced and non-reinforced presentations of inhibitor CS2 might modify the power of CS2 in summation and retardation tests.	GENERAL Rescorla (1969) Zimmer-Hart & Rescorla (1974) Pearce, Nicholas, & Dickinson (1982) Williams et al. (1986)
5.6 Differential conditioning. Stimulus CS2 may acquire inhibitory conditioning with CS1 reinforced trials interspersed with CS2 nonreinforced trials.	SOME DATA Cotton, Goodall, & Mackintosh (1982)
6. Combination of separately trained CSs (3)	
6.1 When two CSs independently trained with the same US are tested in combination, there is more likely to be a summative CR when the CSs are in different than in the same modality.	GENERAL Miller (1971) Whitlow & Wagner (1972) Kehoe, Horne, Horne, & Macrae (1994)
6.2 CSs that are trained with aversive USs may acquire broad tendency to potentiate defensive CRs and suppress appetitive CRs.	GENERAL Bombace, Brandon, & Wagner (1991) Brandon, Bombace, Falls, & Wagner (1991) Brandon & Wagner (1991)
6.3 CSs that are trained with appetitive USs may acquire broad tendency to potentiate appetitive CRs and suppress defensive CRs.	SOME DATA Bower & Kaufman (1963) Hyde & Trapold (1967)

7. Stimulus competition/ potentiation in training (11)	
7.1 Relative validity. Conditioning to X is weaker when training consists of reinforced XA trials alternated with XB nonreinforced trials, than when training consists of XA trials alternated with XB trials, each type reinforced half of the time.	GENERAL Wagner, Logan, Haberlandt, & Price (1968)
7.2 Blocking. Conditioning to CS1-CS2 results in weaker conditioning to CS2, when preceded by conditioning to CS1 than when not.	GENERAL Kamin (1968)
7.3 Unblocking by increasing the US. Increasing the US during CS1-CS2 training increases responding to the blocked CS2.	GENERAL Holland (1984)
7.4 Unblocking by decreasing the US. Responding to CS2 can be increased by decreasing the US during CS1-CS2 training.	GENERAL Dickinson & Mackintosh (1979)
7.5 Overshadowing. Conditioning to CS1-CS2 results in a weaker conditioning to CS2 than that attained with CS2-US pairings.	GENERAL Pavlov (1927)
7.6 Potentiation. With some cues, conditioning to CS1-CS2 can result in a stronger conditioning to CS2 than that attained with CS2-US pairings.	GENERAL Best, Brown, & Sowell (1984)
7.7 Backward Blocking. Conditioning to CS1 following conditioning to CS1-CS2 can result in a weaker conditioning to CS2 than that attained with CS2-US pairings.	SOME DATA Pineño, Urushihara, & Miller (2005)
7.8 Overexpectation. Reinforced CS1-CS2 presentations following independent reinforced CS1 and CS2 presentations, result in a decrement in their initial associative strength.	GENERAL Rescorla (1970)
7.9 Superconditioning. Reinforced CS1-CS2 presentations following inhibitory conditioning of CS1, increase CS2 excitatory strength compared with the case when it is trained in the absence of CS1.	GENERAL Rescorla (1971)
7.10 Rescorla's demonstrations of unequal learning about CSs in compound when they start with different associative strengths.	GENERAL Rescorla (2000)
7.11 Compound conditioning of CS1 preceding a pretrained CS2, caused a pronounced decline in responding to the pretrained CS2.	SOME DATA Egger & Miller (1962) Kehoe, Schreurs, & Graham (1987)

8. CS/ US preexposure effects (11)	
8.1 Latent inhibition. Preexposure to a CS followed by CS-US pairings retard the generation	GENERAL

of the CR.	Lubow & Moore (1959)
8.2 A change of context disrupts latent inhibition.	GENERAL Hall & Channell (1985)
8.3 Presentation of a different CS before conditioning disrupts latent inhibition.	SOME DATA Lantz (1973)
8.4 Context preexposure. Preexposure to a context facilitates the acquisition of fear conditioning to that context.	GENERAL Kiernan & Westbrook (1993)
8.5 US–Preexposure effect. Presentation of the US in a training context prior to CS-US pairings retards production of the CR to the CS.	GENERAL Randich & LoLordo (1979)
8.6 Learned irrelevance. Random exposure to the CS and the US retards conditioning even more than combined latent inhibition and US preexposure.	GENERAL Bonardi & Hall (1996)
8.7 Perceptual learning. Exposure to similar stimuli, CS1 and CS2, leads to faster subsequent acquisition of a discrimination between them.	GENERAL Channell & Hall (1981)
8.8 Hall-Pearce effect. a) Training CS – weak shock leads to slower acquisition of CS – strong shock. b) Brief extinction of the CS after initial training abolishes this effect.	a) GENERAL Hall & Pearce (1979) b) SOME DATA Hall & Pearce (1979)
8.9 An isolated presentation of the US shortly before a standard CS-US pairing impairs CR acquisition.	SOME DATA Terry & Wagner (1975) Terry (1976)
8.10 An isolated presentation of the CS shortly before a standard CS-US pairing impairs CR acquisition as a function of the CS-CS interval.	GENERAL Kalat & Rozin (1973) Best & Gemberling (1977) Best, Gemberling, & Johnson (1979)
8.11 A delay placed after conditioning in Conditioned Taste Aversion might increase latent inhibition	SOME DATA De la Casa & Lubow (2002)
9. Transfer (4)	
9.1 Extinction (see 2.1) Nonreinforced CS-alone training diminishes the CR produced by prior CS-US training.	GENERAL Pavlov (1927)
9.2 Reacquisition. CS-US presentations following extinction might result in faster or slower reacquisition than original training.	GENERAL Ricker & Bouton (1996)
9.3 Counterconditioning. CS-US training with an aversive CS diminishes an appetitive CR otherwise produced by prior CS-US training with an appetitive US (and conversely).	GENERAL Poppen (1970)

	Pearce & Dickinson (1975) Dickinson & Dearing (1979)
9.4 Transfer along a continuum. Discrimination training with CS1 and CS2 that are highly discriminable facilitates subsequent discrimination training with CSs that are more similar to each other.	GENERAL Haberlandt (1971)
10. Recovery (8)	
10.1 Recovery from latent inhibition. LI is attenuated by extensive exposure to the training context following CS-US pairings.	GENERAL Grahame, Barnet, Gunther, & Miller (1994)
10.2 Recovery from overshadowing. Extinction of the CS1 may result in increased responding to the overshadowed CS2.	SOME DATA Kaufman & Bolles (1981) Matzel, Schachtman, & Miller (1985) But not Holland (1999)
10.3 Recovery from forward blocking. Extinction of the blocker CS1 may result in increased responding to the blocked CS2.	SOME DATA Blaisdell, Gunther, & Miller (1999) But not Holland (1999)
10.4 Recovery from backward blocking. Extinction of the blocker CS1 results in increased responding to the blocked CS2.	SOME DATA Pineño et al. (2005)
10.5 External disinhibition. Presenting a novel stimulus immediately before a previously extinguished CS might produce renewed responding.	GENERAL Bottjer (1982)
10.6 Spontaneous recovery. Presentation of the CS after some time after the subject stopped responding might yield renewed responding.	GENERAL Rescorla (2004)
10.7 Renewal. After extinction, presentation of the CS in a novel context might yield renewed responding.	GENERAL Bouton & King (1983) Thomas, Larsen, & Ayres (2003)
10.8 Reinstatement. After extinction, presentation of the US in the context might yield renewed responding.	GENERAL Rescorla & Heth (1975)
11. Higher order conditioning (5)	
11.1 Sensory preconditioning. When CS2-CS1 pairings are followed by CS1-US pairings, presentation of CS2 may generate a CR.	GENERAL Brogden (1939)
11.2 Second order conditioning. When CS1-US pairings are followed by CS2-CS1 pairings, presentation of CS2 may generate a CR.	GENERAL Rizley & Rescorla (1972)

11.3 The number of CS2-CS1 pairings determines whether second-order conditioning or conditioned inhibition is obtained.	SOME DATA Yin, Barnet, & Miller (1994)
11.4 Inhibitory sensory preconditioning is possible.	SOME DATA Espinet, González, & Balleine (2004)
11.5 CS1-CS2 associations mediate conditioning and extinction of CS1 by manipulating CS2 and the US.	GENERAL Shevill & Hall (2004) Holland & Sherwood (2008)

12. Temporal properties (9)	
12.1 Interstimulus Interval (ISI) effects. Conditioning is negligible with short ISIs, increases dramatically at an optimal ISI, and gradually decreases with increasing ISIs.	GENERAL Smith (1968)
12.2 Intertrial Interval effects (ITI). Conditioning to the CS increases with longer ITIs.	GENERAL McAllister, McAllister, Weldin, & Cohen (1974) Spence & Norris (1950)
12.3 Trial spacing effects. When different CSs are reinforced on different trials, conditioning is greater the greater the separation of the like trials.	GENERAL Gallistel & Gibbon (2000) Sunsay, Stetson, & Bouton (2004) Sunsay & Bouton (2008)
12.4 Timing of the CR. CR peak tends to be located around the end of the ISI.	GENERAL Gormenzano, Kehoe, & Marshall (1983)
12.5 Timed responding from the onset of conditioning.	SOME DATA Kehoe, Ludvig, Dudeney, Neufeld, & Sutton (2008).
12.6 Scalar invariance in response timing.	GENERAL Millenson, Kehoe, & Gormenzano (1977)
12.7 Temporal specificity of blocking. Blocking is observed when the blocked CS, is paired in the same temporal relationship with the US as the blocking CS.	SOME DATA Amundson & Miller (2008)
12.8 Temporal specificity of occasion setting. A serial feature-positive discrimination is best when the feature-target interval during testing matches the training interval.	SOME DATA Holland (1998)

12.9 Inhibition of delay occurs with long but not with short ISIs.	SOME DATA Vogel, Brandon, & Wagner (2003)

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